Hydrometeorological Regime of the Kara, Laptev, and East-Siberian Seas

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Federal Service of Russia for Hydrometeorology and Monitoring of the Environment
The Arctic and Antarctic Research Institute
St. Petersburg

With an Introduction by Jamie Morison

Applied Physics Laboratory
University of Washington

Technical Memorandum
APL-UW TM 1-96
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1013 NE 40th Street Seattle, Washington 98105-6698

Distribution Unlimited

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Introduction

This report reviews the hydrometeorological regime of the Kara, Laptev, and East Siberian seas using available Russian and foreign references, data from international expeditions, and modeling results. It was written by the Arctic and Antarctic Research Institute in St. Petersburg, Russia, under contract to the Polar Science Center at the Applied Physics Laboratory, University of Washington. This work was supported by the Arctic Nuclear Waste Assessment Program of the United States Office of Naval Research as part of a study of river plumes on the Russian continental shelves. It is the first step in a joint project aimed at determining the likely distribution of radionuclide contaminants by Russian river plumes through a coordinated effort of data analysis and modeling.

The Ob and the Yenisey rivers are known to have large sources of potential radioactive contamination in their watersheds. If one of these sources leaks, either slowly or catastrophically, into a river, some of the contaminant will come down the river dissolved in the water and some, perhaps a major portion, will be carried down the river bound in the suspended sediment. The river outflow will then disperse over the continental shelf in a plume. What happens at this point is crucial to determining the pathways that the radionuclides will take and whether they might endanger the North American Arctic.

As the river plume spreads over the shelf, the contaminant will be partitioned between the sea water, shelf sediments, and sea ice. The contaminant in solution will mix with the ocean water that the fresh plume overrides. The ultimate fate of this contaminant thus depends on the structure of the plume and its relation to the larger-scale currents and winds. The contaminated sediments will tend to settle out on the shelf, but strong currents can resuspend them and move them episodically offshore or down the coast. Some of the contaminant will be incorporated in sea ice formed on the shelf, either as a solute or attached to sediment. The rate of contaminant uptake by ice is unclear, but is dependent on the concentration, freezing rate, stratification, and mixing in the water. These, in turn, are dependent on the plume distribution and mixing.

This review suggests that river plume circulation on the Russian shelves provides a manifold for distributing contaminants to the whole basin and, because of the tendency for eastward alongshore flow in the Kara, Laptev, and East Siberian seas, a possible direct pathway for contaminants to reach Alaska. The Ob or Yenisey river plume would carry contaminant eastward in the Western Taimyr Current through Vilkitsky Strait and into the Laptev Sea. The Lena River plume would carry it eastward to the East Siberian Sea, where the narrow East Siberian Coastal Current would carry it east into the Chukchi Sea and Bering Strait. The contamination could be carried in solution or as suspended sediment. The transport of suspended sediment would be most vigorous close to shore, where the shallow depth enhances mixing and keeps the sediment in suspension so it can be carried by the coastal currents. Even contamination from dump sites in the Barents and Kara seas can be carried by this coastal pathway. All along the pathway, a portion of the contaminants will be diverted offshore and mix with other water masses of the Arctic. Much of the contaminant trapped in the ice will be carried into the Trans-Polar Drift and exit the Arctic Basin at Fram Strait. The effectiveness of the coastal pathway and the partitioning of the contaminant depend on the dynamics of the river plumes and their relation to the winds, currents, rate of ice formation, and other parameters.

FEDERAL SERVICE OF RUSSIA FOR HYDROMETEOROLOGY
AND MONITORING OF THE ENVIRONMENT
THE ARCTIC AND ANTARCTIC RESEARCH INSTITUTE

HYDROMETEOROLOGICAL REGIME OF THE KARA, LAPTEV AND EAST-SIBERIAN SEAS

(Part 1 of the research subcontract
" Processes of transfer and transformation of contaminants inflowing by continental discharge into the Kara, Laptev and East-Siberian Seas ")

by
Pavlov V.K., Timohov L.A.,
Baskakov G.A., Kulakov M.Yu., Kurazhov V.K.,
Pavlov P.V., Pivovarov S.V., Stanovoy V.V.

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Contents

1. THE KARA SEA

1.1. Physical-geographical characteristics

The Kara Sea is one of the Siberian Arctic Seas. It has an extensive water border with the Arctic Ocean, its largest portion situated at the continental bank, having the characteristics of the marginal continental seas. Its area is equal to 883 000 sq.km., its volume is 98 000 cub.km, with 81.8 % of the area and 77.5 % of the volume constituting a shelf zone with depths up to 200 m.A mean depth of 111 m, and a maximum depth of 620 m are observed in its northern part at the point with the coordinates $80^{0}26'$N and $71^{0}18'$ E [*Baskakov 1978; Dobrovolskiy, Zalogin 1982, Suhovey 1986*].

The line, connecting the Kol'zat Cape with the Zhelaniya Cape at Novaya Zemlya is considered to be the western boundary, separating the Kara Sea from the Barents Sea. Then the boundary passes along the eastern shores of Novaya Zemlya and the Vaigach island, crossing Matochkin Shar, Kara Gate and Yugorsky Shar straits. Of them only Kara Gate strait between the Novaya Zemlya and Vaigach islands is about 45 km wide, up to 119 m deep and 33 km long. The other two straits are narrow (the width in the narrow places up to 2.5 km) and shallow (the depth - up to 36 m). The Novaya Zemlya Archipelago consists of two large islands - the Northern and the Southern and many small ones [*Dobrovolskiy, Zalogin 1982*].

The Kara Sea is separated from the Laptev Sea by the islands of Northern Land Archipelago, and in the straits of the Red Army, Shokal'sky and Vil'kitsky the boundary passes along their eastern periphery. Vil'kitsky strait is the largest one, its length being about 130 km, the least width - 56 km and the depth reaching 210 m. Shokal'sky strait with its length being 110 km has a width of 20-50 km and a depth of 200-250 m. The northern sea boundary goes from the Kol'zat Cape to the Arktichesky Cape (the Northern Land) and the southern boundary - along the mainland coast.

There are many islands in the Kara Sea. The overwhelming majority of them are not large in size and located along the shore, while the most small ones form archipelagos. The most

significant islands are: Beliy, Shokal'sky, Vil'kitsky, Sibiryakov, Dikson, etc. Several comparatively large islands (Schmidt, Ushakov, Vieze) are situated in the north of the sea.

The coastline of the Kara Sea is complicated and irregular. The eastern shores of Novaya Zemlya are rugged by numerous fiords. The mainland coast is considerably rugged too, where the Baidaratskaya and Ob' Gulfs cut deep inland, between which the Yamal peninsula protrudes far into the sea and to the east there are large bays: Gydansky, Yenisey and Pyasinsky. The western coast of Northern Land is less irregular.

The coast of the Kara Sea belongs to different morphological types of the shores. These are predominantly the abrasion ones but there are also observed the accumulation and ice shores. The eastern shores of Novaya Zemlya - are cliff-like and hillocky. The mainland coast is lowland, gently sloping in some places and steep in the other areas.

A characteristic feature of the bottom topography of the Kara Sea is the presence of deep-water troughs of St. Anna (depths - up to 610 m) and Voronin (depths - up to 450 m). Between them there is the Central Kara Upland with the depths of less than 50 m. Along the Novaya Zemlya coast there is the Novozemel'sky hollow with a depth of more than 400 m.

The southern and the eastern parts of the sea adjacent to the mainland are shallow. Here the sea bottom is crossed by numerous small hollows, divided by the sills of a different height. The bottom is relatively level in the central sea areas.

On the whole, about 64% of the Kara Sea area has depths less than 100 m and only 2% - more than 500 m [*Dobrovolskiy, Zalogin 1982; Soviet Arctic 1970; Suhovey 1986*].

A complicated character of the bottom topography, an irregular coastline and the presence of islands govern in many respects a complicated character of the water structure and the hydrological regime of the Kara Sea.

1.2. Meteorological regime and climate.

The Kara Sea is located north of the Polar Circle, being directly influenced by the cold Arctic Ocean from the north and a

vast Asian continent from the south. A high-latitudinal position of the sea governs a peculiar radiation regime.

1.2.1. Radiation

The annual influx of total solar radiation to the surface of the Kara Sea is 2700-3000 Mj/sq.m. The maximum of solar radiation income is in May-June (about 50% of the annual sum), but due to a high reflectivity of snow and ice, about 60% of the radiation is reflected back to the atmosphere and only 1000-1500 Mj/sq.m a year is absorbed. From October to April the radiation balance (difference between absorbed solar radiation and effective radiaton) is negative, reaching 80 Mj/sq.m, but, on an average, over the year it is positive, varying from 200 Mj/sq.m in the northern part of the sea to 500-600 Mj/sq.m in its southern part [*Chernigovsky, Marshunova 1965*]. Fig 1.1 presents distribution of the annual radiation balance. As is evident, the radiation balance of the underlying surface over the year is positive. Fig 1.2 presents maps of the radiation balance distribution (a) - for January and (b) - for July.

1.2.2. Underlying surface

The underlying surface plays an important role in the climate formation in the Kara Sea. The Kara Sea is ice-covered much of the year. In winter during polar night the ice of the Kara Sea, covered by snow and the northern part of the continent, present a uniform character of the underlying surface. Ice cover smoothes to some extent the climatic contrasts between its separate regions. Ice makes difficult the heat exchange between the ocean and the atmosphere, but does not exclude it, that is why the climate of the Kara Sea in winter is a little warmer than the climate of the adjacent land regions.

The ice melt in the southern regions starts at the end of May. The ice decay in the south-western sea - in July. In the northern sea ice persists during all summer, resulting in a significant air temeprature drop, enhanced humidity and increased frequency of fogs. In mid-September a stable ice formation in the north-eastern Kara Sea begins, and in mid-October the ice cover forms already in the Ob'-Yenisey region [*Climate features 1985*].

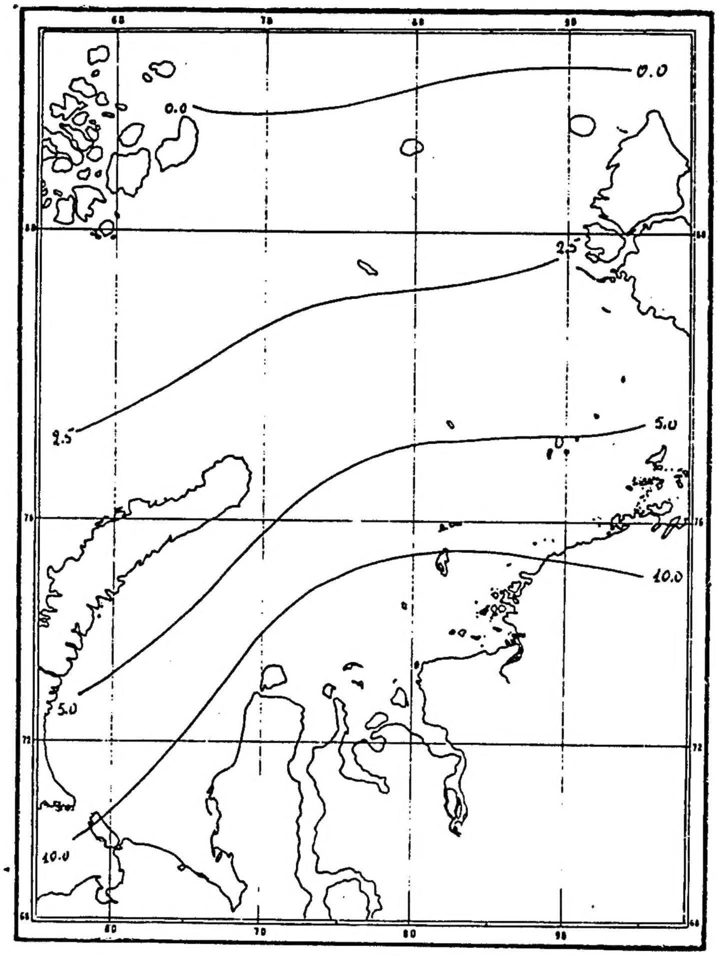


Fig 1.1. Distribution of the annual radiation balance (Kkal/year·cm^2) of the underlying surface in the Kara Sea [Chernigovsky, Marshunova 1965].

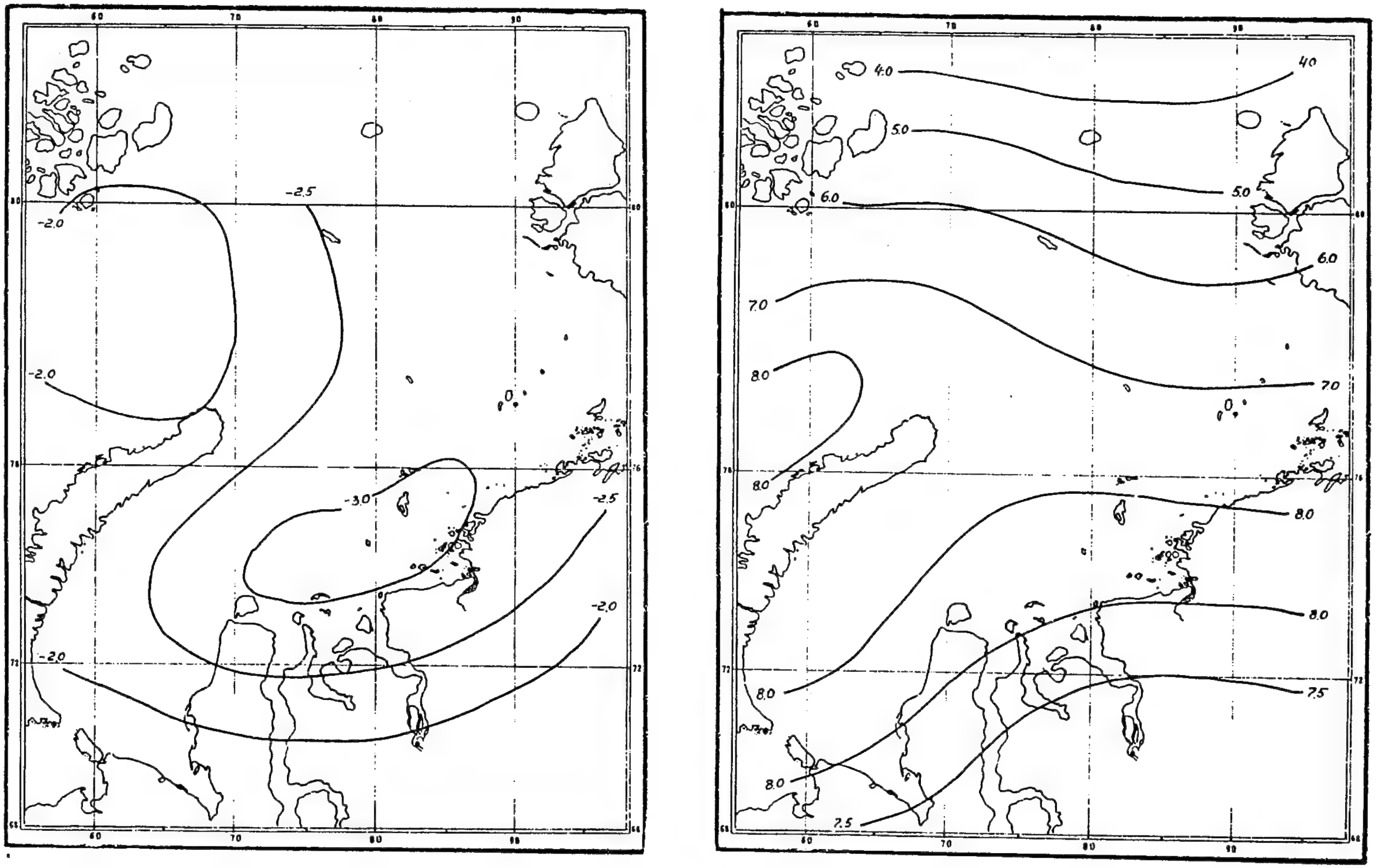


Fig 1.2. Distribution of the radiation balance
(Kkal/month·cm^2) of the underlying surface in the Kara Sea
(a) - for January and (b) - for July.
[Chernigovsky, Marshunova 1965].

1.2.3. Atmospheric circulation

The atmospheric circulation and associated distribution of pressure fields along with the radiation regime of the Kara Sea and its underlying surface are considered to be one of the main factors, forming the climate of this sea.

In winter (Fig. 1.3.a) the atmospheric circulation in the Western Arctic is governed by the presence of two centers of the atmosphere action: the Icelandic Low and Siberian High. The Kara Sea at this time is being influenced by an extensive trough of the Icelandic Low, and over the north-eastern part of the Asian continent there is a stable domain of high pressure [*Soviet Arctic 1970; Prik 1959*]. The main trajectories of the cyclones, moving from west to east and inducing sharp air temperature increases and stronger winds, are related with the trough of the Icelandic Low. The number of such cyclones in each month varies from 5 to 7 [*Ragozin, Chukanin 1961*]. The indicated distribution of pressure fields governs the dominance of the winds with a southern component over the sea in winter, which is confirmed sufficiently convincingly by the data on the frequency of air transports [*Atlas of the Arctic 1985*], given in Fig. 1.4.a.

In spring the pattern of the pressure field changes [*Soviet Arctic 1970*]. The Siberian High is destroyed and replaced by the depression, which is not deep, but extensive. The trough of the Icelandic Low is gradually filled and in May it disappears completely (Fig. 1.3.b.). The presence of a small gradient field of decreased pressure over the Kara Sea significantly reduces the stability of the wind flows. An insignificant prevalence of the wind of eastern, south-eastern directions is observed in the north-eastern sea and of western, north-western in its south-western part (Fig. 1.4.b.).

In summer the character of the pressure field as compared with the winter one, changes quite oppositely [*Soviet Arctic 1970*]. An active cyclonic activity develops over the continent, and over the Kara Sea there forms an area of increased atmospheric pressure with an anticyclonic center over the Barents Sea (Fig. 1.3.c.). Due to this in summer the winds of northern and north-eastern directions prevail over the Kara Sea (Fig.

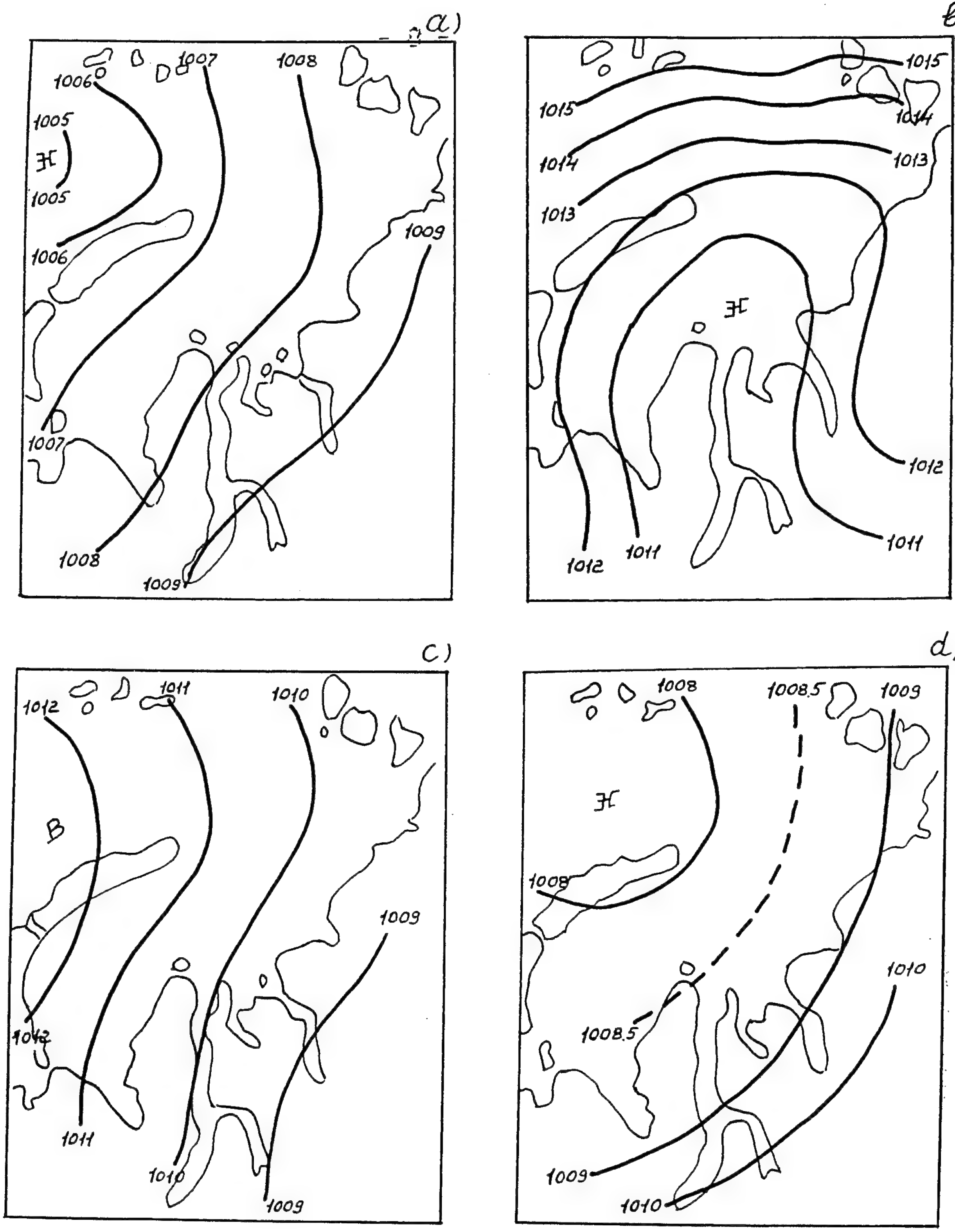
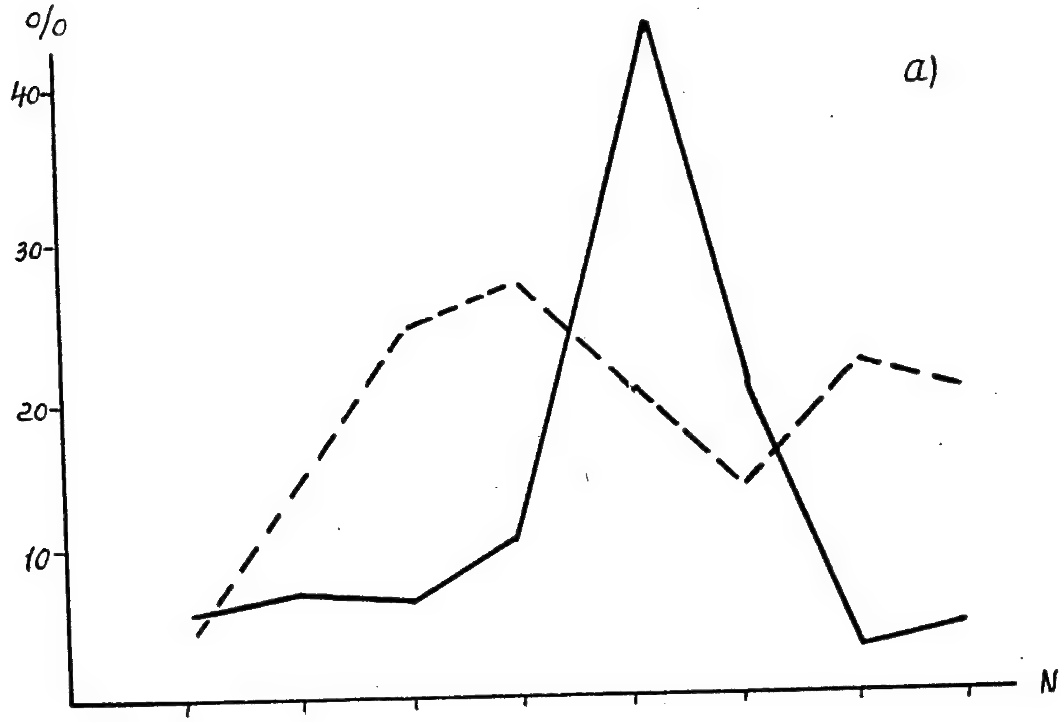


Fig. 1.3. The seasonal distribution of pressure fields over the Kara Sea
a) in winter, b) in spring,
c) in summer, d) in autumn.
[Soviet Arctic 1970]



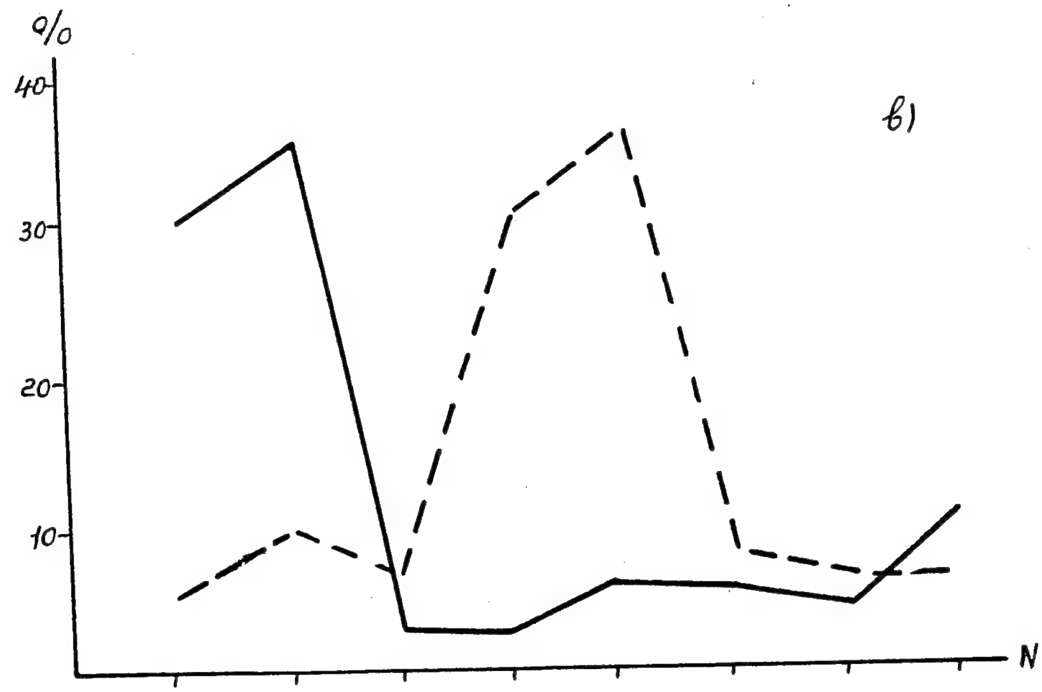


Fig. 1.4. Multiyear occurrence frequency of the directions of air flows over the Kara Sea

a) ——— winter, ----- spring,

b) ——— summer, ----- autumn.

[Atlas of the oceans. The Arctic Ocean. 1980]

1.4.c.), that is, they have a well-pronounced character of the summer monsoon [*Atlas of the Arctic 1985*].

In the fall there is a transition to the winter type of the distribution of pressure fields [*Soviet Arctic 1970*]. In September over the Barents Sea and from October also over the Kara Sea there appear surface cyclonic centers, which gradually become deeper and join with the developing trough of the Icelandic Low. In October this trough is already quite evident and the number of cyclones, moving through this trough from the west, increases to four [*Ragozin, Chukanin 1961*]. A stable center of high pressure forms over Siberia (Fig. 1.3.d.). From September to October the frequency of the winds, typical of the winter period, appreciably increases and in October the winds of the winter type become already predominant, that is, the air flows from the continent to the sea become stable (Fig. 1.4.d.).

1.2.4. Wind

Mean wind speeds over the area of the Kara Sea change insignificantly from season to season and the annual amplitude does not exceed 1-3 m/s. The largest mean wind speeds are observed in the fall and in winter (8 m/s), which is attributed to enhanced cyclonic activity during this period. In summer the wind speeds decrease to 5 m/s. The wind speed depends on its direction. Most strong, as a rule, appear to be the winds of western directions. In the coastal part of the southern sea the largest speeds are observed at southerly winds. In the south-western part of the sea moderate winds (6-8 m/s) have the largest occurrence frequency. Storm winds (more than 15 m/s) are most frequent (up to 8-9 days a month) during the colder part of the year at west, south-west and south winds, being accompanied by an increased air temperature and drifting snow. In summer the storms are observed very seldom (1-2 days for a month), mainly at north and north-east winds, being accompanied by the air temperature decrease. Below, Table 1.1 presents data with the maximum number of days with strong winds for different regions of the Kara Sea. On the whole, the sea is characterized by a large frequency of weak winds, the speed of which does not exceed 5 m/s. In summer their frequency is about 50% [*Soviet Arctic 1970;*

Climate features 1985].

Table 1.1

Mean and maximum number of days with strong wind
(more than 15 m/s)

Regions	Months												
	1	2	3	4	5	6	7	8	9	10	11	12	Year
South-western	7	5	5	6	4	3	2	3	5	6	8	7	61
Kara Sea	14	14	9	14	7	7	4	5	7	14	14	12	121
North-eastern	9	7	7	7	4	3	2	3	6	7	8	9	72
Kara Sea	15	18	17	17	9	10	7	8	11	16	13	19	160
Eastern	5	4	3	3	2	3	1	2	4	3	4	3	37
Kara Sea	11	7	9	6	3	8	2	6	7	6	9	9	83

Note: mean - in the numerator, maximum days with strong wind - in the denominator.

1.2.5. Thermal regime

The features of the geographical location of the Kara Sea and the atmospheric circulation over it create distinct differences in the air temperature regime over different sea regions. Mean annual air temperature over the south-western sea is by 5-7 degrees higher than over the north-eastern one. In the south-western sea the highest and lowest temperatures are not recorded during the central winter and summer months, but 1-2 months later. The coldest month is February, the warmest - August. In the north-eastern sea the most warm month is July, and the temperatures of January and February are close [*Soviet*

Arctic 1970]. In winter sharp air temperature differences are often recorded. Almost annually during one of the central winter months the air temperature increase is observed, as compared with the adjacent months ("warm core"), which is related with the heat advection increase over the North Atlantic. Since this increase can fall on different winter months, the mean multiyear curve of annual temperature variations has a typical for the Kara Sea appearance without a well-pronounced annual minimum [*Petrov 1959*].

In winter, as is seen from Table 1.2, the character of the thermal field over the Kara Sea changes little from month to month [*Prik 1959; Climate features 1985*]. Mean monthly January temperature in the south-western sea is -21^{0}C, and in the eastern part - -28.4^{0}C. In July the air temperature over the Kara Sea is practically everywhere positive and only in the northern sea in summer it is about zero.

A stable air temperature transition across 0 degrees in the fall in the northern Kara Sea occurs during the second 10-day period of August, and in the south-western part - in late September, early October [*Soviet Arctic 1970*]. Such late air temperature transition across 0 degrees is connected not only with the advection of warm air masses in cyclones, but also with the warming effect of warm water, incoming to the Kara Sea from the Barents Sea.

1.2.6. Cloud, humidity, precipitation

In accordance with the atmospheric circulation conditions the cloud cover of the Kara Sea is characterized by well-pronounced annual variations with a maximum in summer and minimum in winter. Mean cloud cover in January is equal to 50-60%, and from June to October it is 80-90%. More contrast appears to be the distribution of frequency of clear and cloudy weather during the year. From December to March 5-8 clear days are observed, on an average, over the north-eastern sea and 3-5 days - over the south-western part. In summer 1-3 days, on an average occur over the sea during the month. The occurrence frequency of overcast sky during the navigation period is 80-90% [*Soviet Arctic 1970*].

Table 1.2

Mean monthly (1), absolute minimum (2), absolute maximum (3) of air temperature (deg.C)

Regions	N	Months 1	2	3	4	5	6	7	8	9	10	11	12	Year
South-western Kara Sea	1	-21.0	-24.4	-21.7	-16.8	-7.7	-0.1	4.3	5.2	1.6	-6.1	-16.3	-21.7	-10.4
	2	-51	-54	-52	-38	-33	-15	-6	-5	-21	-30	-41	-52	-54
	3	1	2	2	4	10	25	28	26	18	10	3	1	28
North-eastern Kara Sea	1	-26.3	-25.5	-24.4	-16.9	-7.8	0.1	0.6	0.9	1.3	-7.0	-18.0	-23.1	-11.5
	2	-52	-52	-48	-41	-32	-18	-4	-3	-22	-31	-45	-48	-52
	3	0	0	-2	3	10	20	26	24	17	7	2	-1	26
Eastern Kara Sea	1	-28.4	-27.0	-28.0	-21.3	-9.6	-1.2	0.7	0.0	-3.2	-11.3	-20.8	-25.8	-14.7
	2	-53	-49	-50	-41	-32	-18	-5	-11	-21	-32	-40	-47	-53
	3	1	0	-3	0	2	13	16	15	6				

Air humidity depends first of all, on moisture content of the air mass and air temperature. A relative humidity over the Kara Sea is large throughout the year, but its largest values are recorded in summer, being 85-95 %. And the largest frequency of precipitation for all seasons is connected with such high humidity. However, in spite of its large occurrence frequency, the total sum of precipitation is insignificant. From 250 mm in the northern part of the sea to 400 mm in its south-western part fall out during the year. The structure of precipitation significantly changes from season to season. In the winter months it falls out in the solid form. The fraction of mixed and liquid precipitation in summer is small, being only 12 %.

1.2.7. Dangerous weather phenomena

Along with the considered features of the climatic regime of the Kara Sea, one of the most typical features appears to be a large frequency of fogs in summer and drifting snow in the colder part of the year. Fogs, as a rule, are related with the advection of warm and moist air to the cold underlying sea surface . Drifting snow is observed mainly at the wind directions, prevailing for this area and at any negative air temperature. With the wind increase to a storm one, air temperature decrease and a significant increase at the cyclone exit from the west, drifting snow is most dangerous. In these cases, as during intensive fogs, the horizontal visibility decreases to several meters. Table 1.3 presents a maximum number of days with fogs for some regions in the Kara Sea.

1.3. Continental outflow to the Kara Sea

One of the most significant features of the Kara Sea is a strong continental outflow. The volume of the river run-off to the sea is about 1525 cu.km [*Ivanov 1976*].

In this section there were used monographs [*Antonov 1962; Antonov, Maslayeva 1965; Domanitsky et al. 1971; Soviet Arctic 1970*] and handbooks: State Water Cadastre. Annual data on the regime and resources of surface water of the land and Resources of surface water of the USSR. Main hydrological characteristics.

Table 1.3

Mean and maximum number of days with fogs

Regions	Months 1	2	3	4	5	6	7	8	9	10	11	12	Year
South-western Kara Sea	5	7	5	7	8	14	18	12	12	7	4	4	103
	13	12	12	16	19	20	26	22	19	19	12	10	200
North-eastern Kara Sea	4	5	6	5	6	13	19	13	10	5	3	3	92
	11	11	13	10	12	21	29	24	18	14	10	8	178
Eastern Kara Sea	1	2	2	2	3	9	20	20	12	3	1	1	76
	8	6	12	11	11	11	26	27	23	9	10	6	166

Note: mean - in the numerator, maximum days with fogs - in the denominator.

The rivers Ob', Yenisey, Pyasina, Pur, Taz and numerous smaller rivers fall into the Kara Sea. Ob' and Yenisey are the largest rivers at the territory of Russia. Fig. 1.5 presents the distribution of mean multiyear volume of the run-off of the five main rivers and the contribution of each river into the total outflow can be well seen.

1. The Ob' river is the third by the stream-flow rate after Yenisey and Lena, its length is 3650 km (together with Irtysh - 5410 km). The area of the water catchment basin of the Ob' river is 2990 sq. km, the total number of the rivers of the basin is more than 150 000, there is a lot of lakes and swamps. The river alimentation is mainly by snow. When falling into the Ob' Gulf, Ob' forms a delta with an area of more than 4000 sq. km. The Ob' Gulf extends over more than 800 km.

In the upper course of the river the spring flood begins in early April, in the lower course - from late April- early May. The wave height during the flood in the lower course of the river exceeds 5 m.

Water discharge is measured at the gauging section of the river (p. Salekhard) from 1930. Mean transports change from 1470 cu. m/s near Barnaul to 12600 cu.m/s near Salekhard. Maximum discharges are, respectively, 9690 and 43400 cu.m /s. The diagram of mean multiyear transports is given in Fig. 1.6. Fig. 1.7 presents a percentage ratio of mean monthly mean multiyear discharges. The main portion of the river run-off is transported during the spring-summer period of the flood and its drop, i.e. more than 75% of the total volume of the run-off is in May-September. Mean annual run-off is about 400 cu.km. Annual run-off of suspended sediments is about 16 mln.t, and the entire solid run-off is avout 50 mln t.

Fig. 1.8 presents diagrams of the variability of mean annual and mean monthly (June) river discharges. Some periodicity in the fluctuations of the discharge value is observed and the periods of about 8, 12.5 and 30 years are found out. Also, there is a tendency towards the increase of mean annual and mean monthly

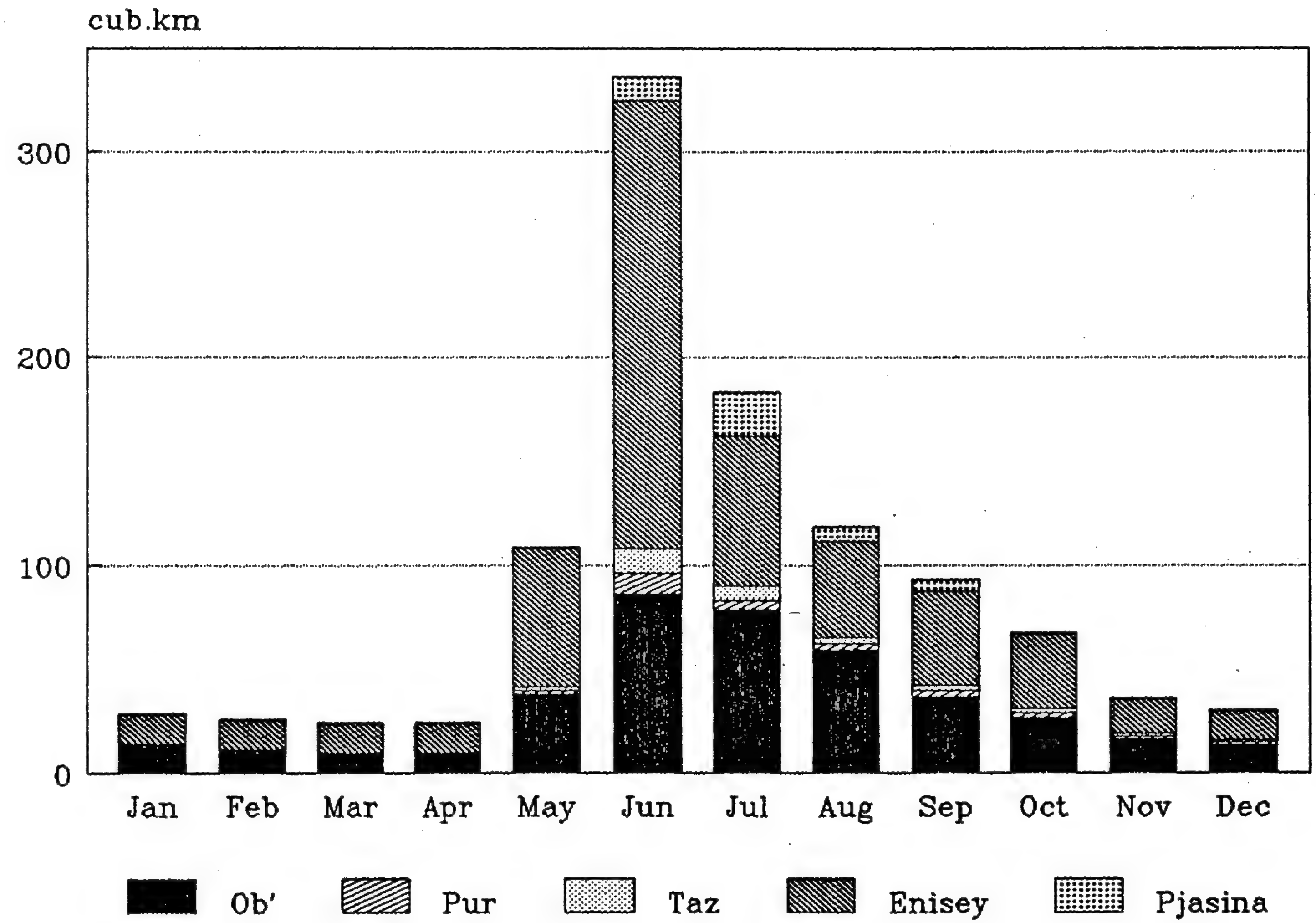
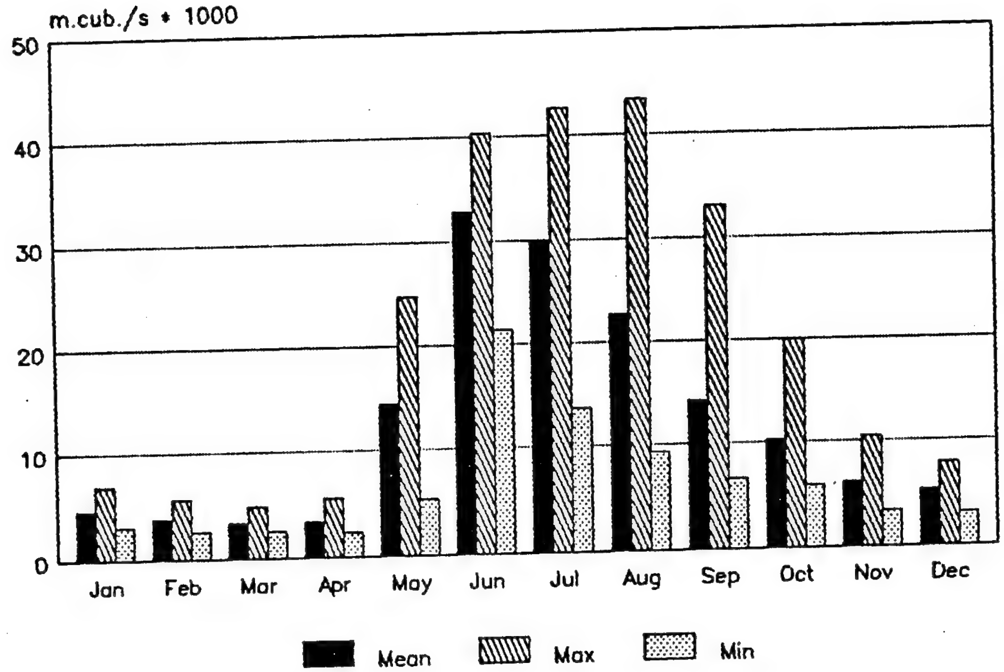


Fig. 1.5. Distribution of mean multiyear volume of the river run-off into the Kara Sea

r. OB'



rr. Pur, Taz

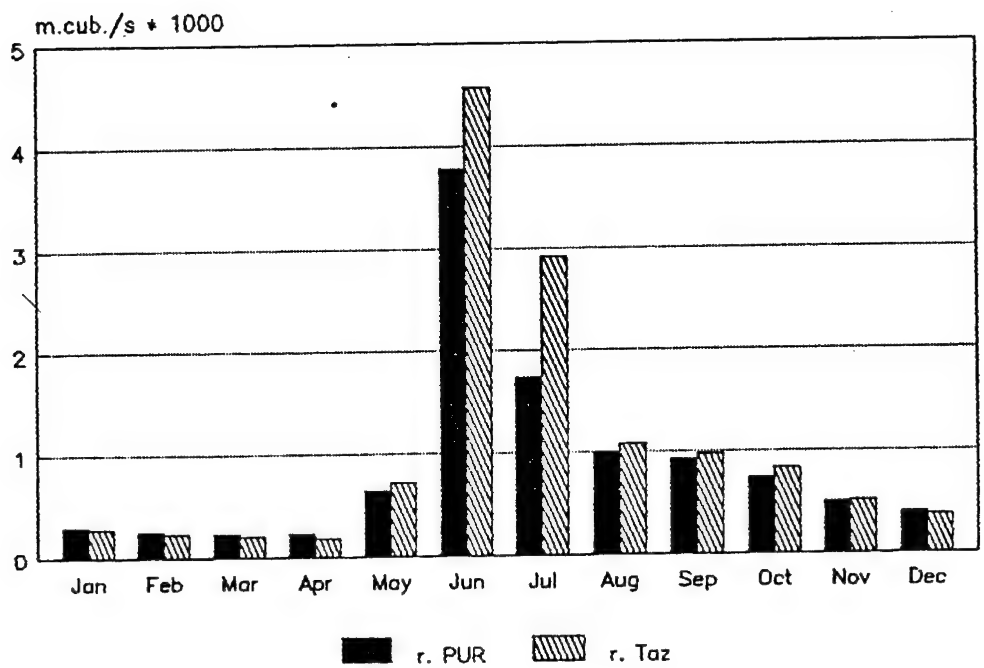


Fig. 1.6. Diagram of mean multiyear water discharges of the rivers Ob', Pur and Taz.

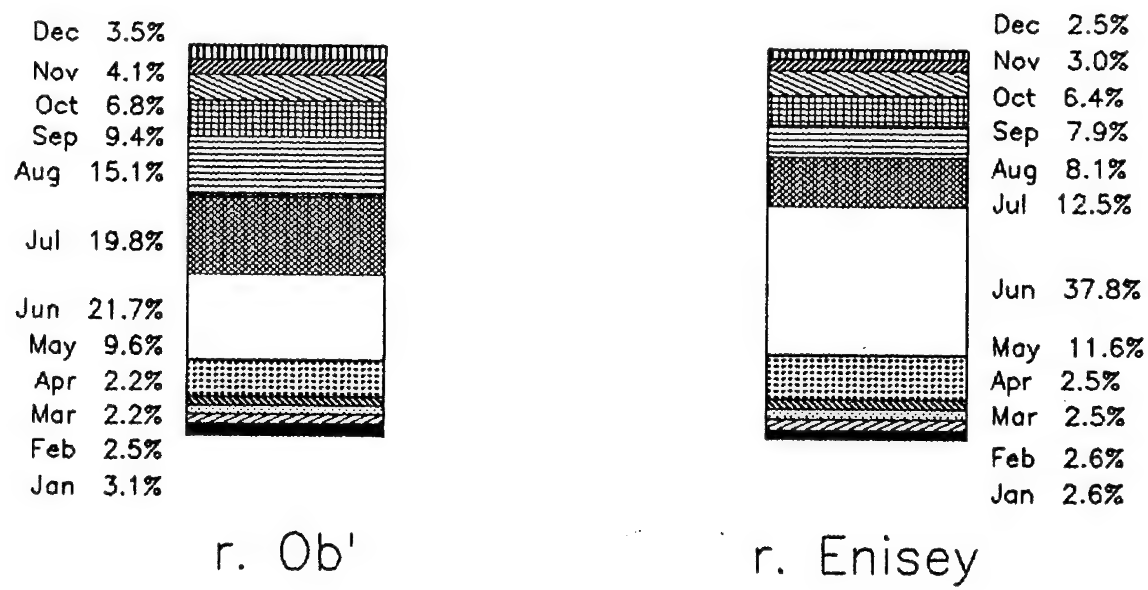


Fig. 1.7. A percentage distribution of the mean multiyear water discharge of Ob' and Yenisey.

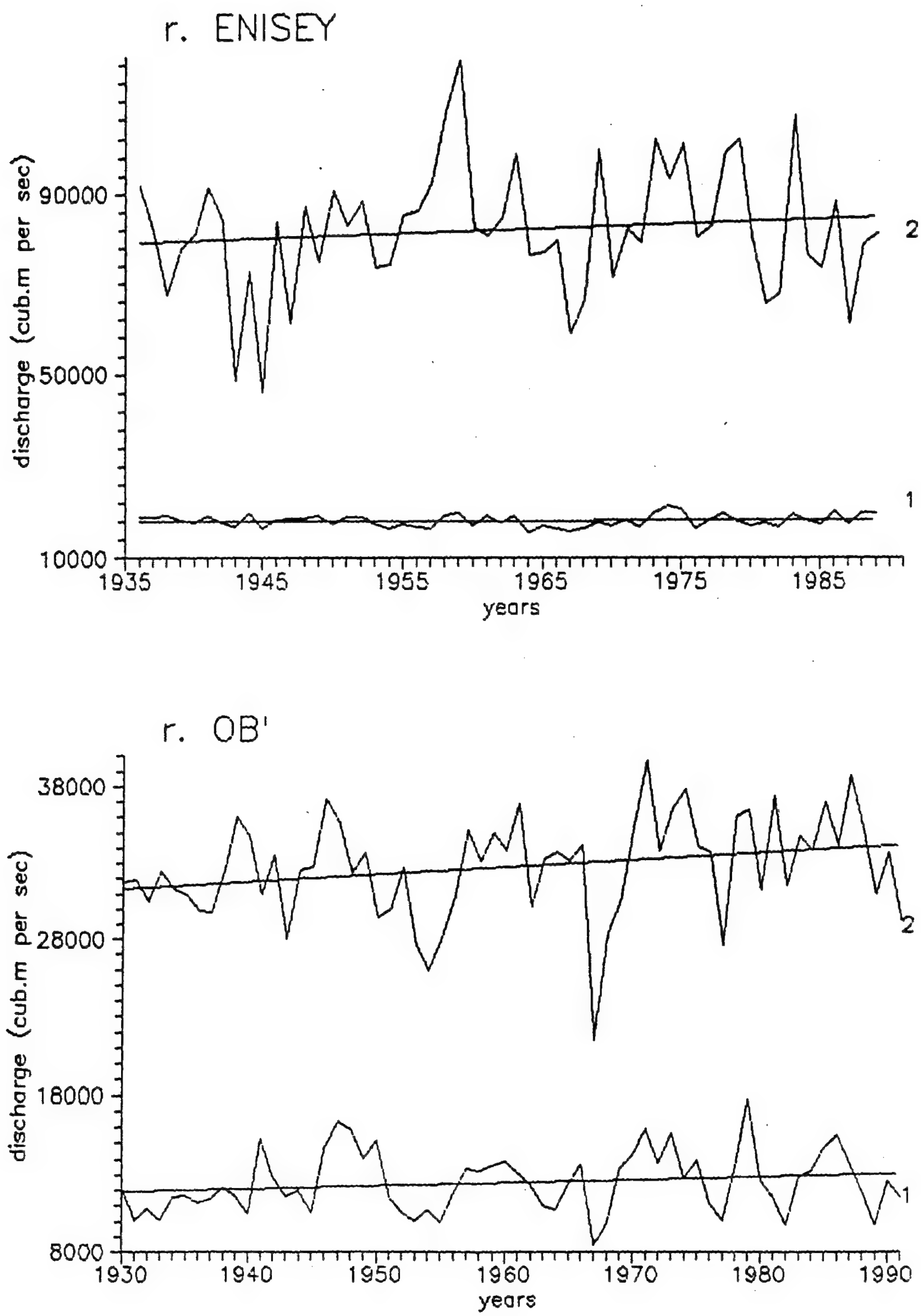


Fig. 1.8. Diagram of the variability of mean annual (1) and mean monthly June (2) discharges of Ob' and Yenisey.

(June) water discharges.

2. The Pur river is 389 km long with an area of the water catchment Basin 112 000 sq. km. It falls into the Taz Gulf. The alimentation of the river is due to rain and snow. It freezes in November and the ice break-up is in May.

Water discharges are measured at the gauging section of the river (p. Samburg) from 1939. Mean water discharge is about 900 cu.m/s and maximum - up to 5180 cu.m/s. The diagram of mean multiyear discharges is given in Fig. 1.6. The main run-off volume falls on June-September. Mean annual run-off of Pur is about 30 cu. km.

3. The Taz river is 1401 km long with the area of the water catchment Basin of 150 000 sq. km. It falls into the Taz Gulf, forming a shallow bar. The alimentation of the river is mainly due to snow (54%) with a large portion of ground water (27%). The spring flood in the upper course occurs from late April to September, in the lower course - from late May to September. The wave height of the flood in the upper course is up to 6 m, in the lower course - up to 3 m.

Water discharges are measured at the gauging section of the river (p. Sidorovsk) from 1962. Mean water discharge is about 1060 cu.m/s and maximum - up to 6630 cu.m/s. The diagram of mean multiyear discharges is given in Fig. 1.6. The main discharge volume, similar to Pur, is in June-September. Mean annual run-off of Taz is about 34 cu.km. It freezes in October and the ice break-up is in late May-early June.

4. The Yenisey river has the largest stream-flow rate, its length is 4102 km from the source of Large Yenisey (4092 km - from Small and Large Yenisey merging). The length of Yenisey Bay is 225 km to the Sopochnaya Karga cape. Below the Ust' Port p. Yenisey forms a delta. The area of the water catchment basin of the river is 2580000 sq. km, including more than 200000 rivers, many lakes and swamps. Over the largest part of the basin there is multiyear frozen rock. The alimentation of the river is mixed with the dominance of the snow one (about 50%), rain portion being 36-38%. Underground alimentation is up to 16% in the upper reaches of Yenisey.

Water discharge is measured at the gauging section of the

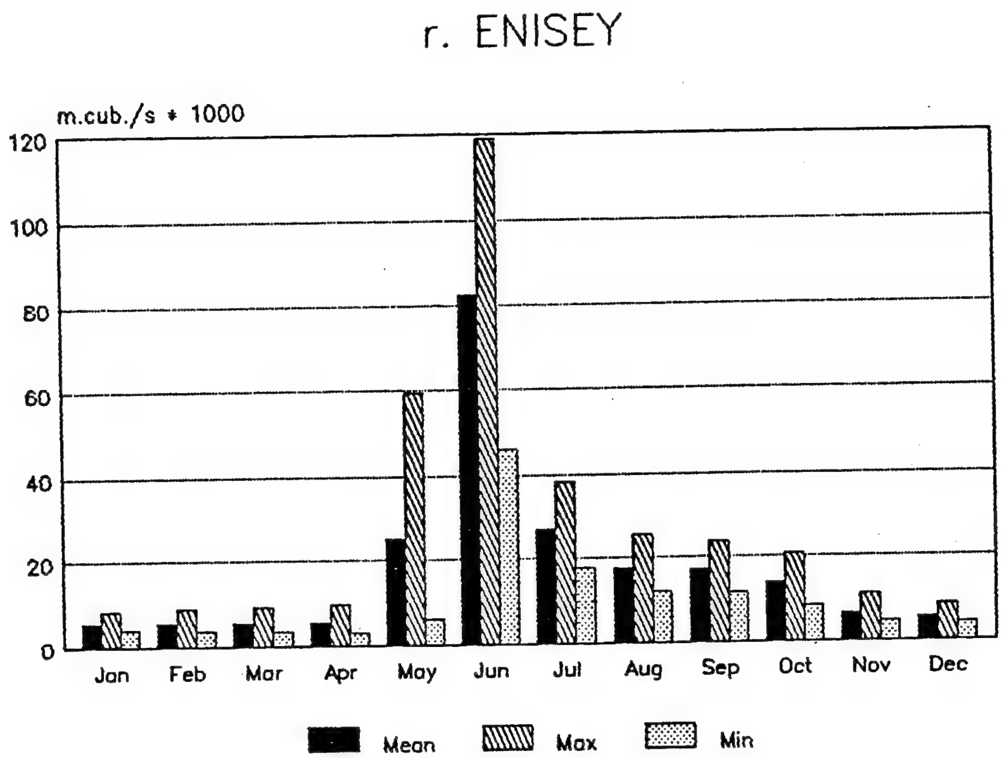
river (p. Igarka) from 1936. There are an extended spring flood and summer floods.The spring flood begins in May-early June. The wave height of the flood reaches 28 m in the lower course of the river, decreasing to 12 m toward the mouth (Ust'-Port). In winter there is a sharp reduction of the run-off, but the level drops slowly due to the development of ice jams. Fig. 1.7 presents a percentage ratio of mean monthly mean multiyear discharges. The main portion of the river run-off is transported during the spring-summer period of the flood and its fall, that is, 78% of the total run-off volume is in May-September. Mean water discharge changes from 1010 cu.m/s near the Kyzylkum town to 18200 cu.m/s near Igarka. Maximum discharge near Igarka is up to 154000 cu.m/s. The diagram of mean multiyear discharges is given in Fig. 1.9. Mean annual run-off of Yenisey is about 630 cu.km.

Fig. 1.8 presents diagrams of the variability of mean annual and mean monthly (June) discharges of the river. The periodicity is somewhat different from Ob', there is a well-pronounced period of about 13.5 years. Also, a tendency towards the increase of mean annual and mean monthly (June) water discharges is traced, but this tendency is a little less, as compared with Ob'.

The river freezing begins in the lower reaches in early October. It is characterized by an intensive formation of intrawater ice and an ice drift. The ice cover becomes stable in the lower reaches from late October. The ice break-up in the upper course occurs in late April, in the lower one - in early June. The spring ice drift is accompanied by ice gorges.

5. The Pyasina river is 818 km long with the area of the water catchment basin of 182000 sq. km. It flows out of the Pyasina lake. When falling into Pyasina Bay, it forms an estuary with a bar region. There are more than 60 000 of lakes at the territory of the basin. The river alimentation is mainly by snow - up to 60%. The river freezing occurs in late September-early October. In winter the river freezes down to the bottom. The ice break-up is in June.

Water discharge is measured at the gauging section of the river (p. Ust'-Tareya) from 1961. Mean water discharge changes from 560 cu.m/s in the source to 2600 cu.m/s in the mouth. The



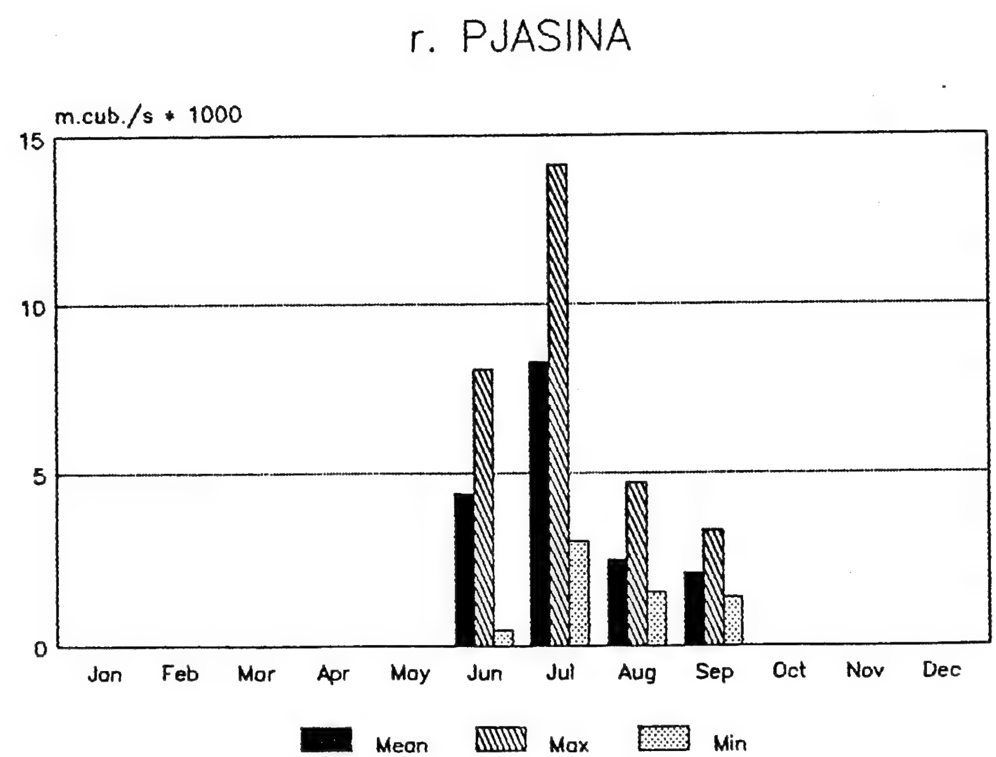


Fig. 1.9. Diagram of mean multiyear water discharges of Yenisey and Pyasina.

diagram of mean multiyear discharges is given in Fig. 1.9. Mean annual run-off of Pyasina is about 50 cu.km.

1.4. Water masses and thermohaline structure

The water structure of the Kara Sea is governed by the water inflow from the Arctic Basin and the Barents Sea, as well as the continental run-off and the waters, forming as a result of their mixing and transformation directly in the Kara Sea [*Nikiforov, Shpaikher 1980; Timofeev 1960; Timofeev, Panov 1962*].

The water structure in the south-western Kara Sea is governed by surface Arctic water of the Kara Sea, Barents water incoming through the southern Novozemel'sky straits and by bottom water, forming as a result of winter cooling and water salination with ice formation. The Barents Sea water as the most dense one submerges under the surface Arctic water. A characteristic feature of this region appears to be the water temperature increase at the depths, by which the lower boundary of the spreading of the winter convective mixing is determined. The Barents Sea water is underlied by bottom water.

The northern Kara Sea is characterized by an intensive influence of deep Atlantic water, penetrating the Kara Sea from the Arctic Basin by deep troughs of St. Anna and Voronin. What is typical of this region is that the layer of surface Arctic water covers the layer of winter surface water. The depth of the location of the minimum temperature layer indicates the boundaries of the winter convection extent. Surface water is underlied by Atlantic water. Bottom water with negative temperatures and a little higher salinity spreads under a layer of Atlantic water.

The remaining part of the Kara Sea is under a prevailing influence of the continental run-off water. A relatively warm and strongly desalinated water of the continental run-off flows onto a more dense bottom water.

Thus, one usually distinguishes between the following water masses in the Kara Sea [*Nikiforov, Shpaikher 1980; Timofeev 1960; Timofeev, Panov 1962*]:

1). Surface water of the Arctic Basin is a water mass,

located in the upper layers, which differs by a salinity increase with depth and a temperature, close to the freezing temperature at this salinity. This water, on the whole, is characterized by rather small seasonal changes of temperature and salinity.

2). Surface water of the Kara Sea is a water mass, located in the surface sea layer, characterized by significant seasonal fluctuations of temperature and salinity. In the wintertime this water is subjected to cooling and salination due to ice formation. A convective mixing, developing with cooling, contributes to water salination and an increased uniformity of the entire layer, which in shallow regions can extend to the bottom. The temperature of this water is close to the temperature of freezing at a given salinity. In those cases when the ice cover due to the dynamic reasons is exported, the ice formation and, hence, the salination of water can occur many times. As a result of these processes more saline and colder water can form, i.e. more dense, than ice-covered water. Such water was called shelf water. Naturally, more dense water submerges, forming an intermediate layer of cold water. In deep - sea areas the convection depth is restricted by the depth of Atlantic water. The thickness of the layer and the position of the boundary of the surface sea water extent depend both on the degree of the fall-winter cooling and the water inflow from the Arctic Basin and the Barents Sea.

The surface water of the Kara Sea can interact with the Barents Sea water, river or surface Arctic water of the Arctic Basin. As a result there are water modifications. For example, a summer warming and desalination of surface water by river water form modified summer waters.

3). Barents water is water of the Atlantic origin with high salinity during all seasons of the year and vertical temperature homogeneity, coming into the Kara Sea northward of the Zhelaniya Cape and through Southern Novozemel'skiye straits.

4). Atlantic water comes into the Kara Sea from the Arctic Basin by deep water troughs of St. Anna and Voronin. Due to a high salinity more dense Atlantic water gradually submerges under surface Arctic water and extends along the continental slope of

Eurasia.

5). River water has a large influence on the hydrological regime of the Kara Sea. The annual run-off volume, versus the entire sea area gives a layer of fresh water 152 cm thick [*Antonov 1964*].

Main characteristics of the water masses are given in Table 1.4.

A typical distribution of water masses in the surface layer in winter and in summer is shown in Fig.1.10.1.

The distribution of water masses has not only a seasonal but also an interannual variability, connected with the effect of atmospheric processes - the dominance of the Icelandic Low or the Arctic High [*Nikiforov, Shpaikher 1980; Shpaikher, Fedorova, Yankina 1972*].

In the years of the prevailing effect of the Arctic High the transport of water masses from south to north is developed, the outflow of river water to the Kara Sea increases, the flow of the Barents Sea water decreases. The surface water salinity reduces. The sea level increases and the thickness of the surface water layer exceeds the norm. Deep Atlantic water is situated closer to the surface (Fig.1.10.2.).

In the years of the prevailing effect of the Icelandic Low the water mass transport from west to east prevails in the Kara Sea, which results in the increase of the income of Barents water into the western part of the sea and the outflow of surface Arctic water. Respectively, the sea level drops, the thickness of the surface water layer decreases and the salinity of surface water increases. The location of Atlantic water deepens (Fig.1.10.3).

The distribution of water masses is closely connected with the thermohaline and hydrochemical regimes of the sea, as well as with the water dynamics.

A high latitudinal position of the Kara Sea governs a small inflow to sea surface of the radiation energy and its significant seasonal variability.

Seasonal variability of the thermal state of surface water is governed both by the annual variations of the radiation

Table 1.4.

Main characteristics of the water masses of the Kara Sea.

Water massa		The surface water of the Arctic Basin	The surface water of the Kara Sea	The modification summer surface water	The river water	The Barents Sea water	The atlantic water
Winter	Temperature, °C	-1.80	-1.40	–	0	-1.90	2.25
	Salinity, ‰	32.00	25.00	–	1.0	35.60	34.98
Summer	Temperature, °C	-1.80	-1.40	7.00	11.70	6.00	2.25
	Salinity, ‰	32.00	22.00	24.50	1.0	35.30	34.98

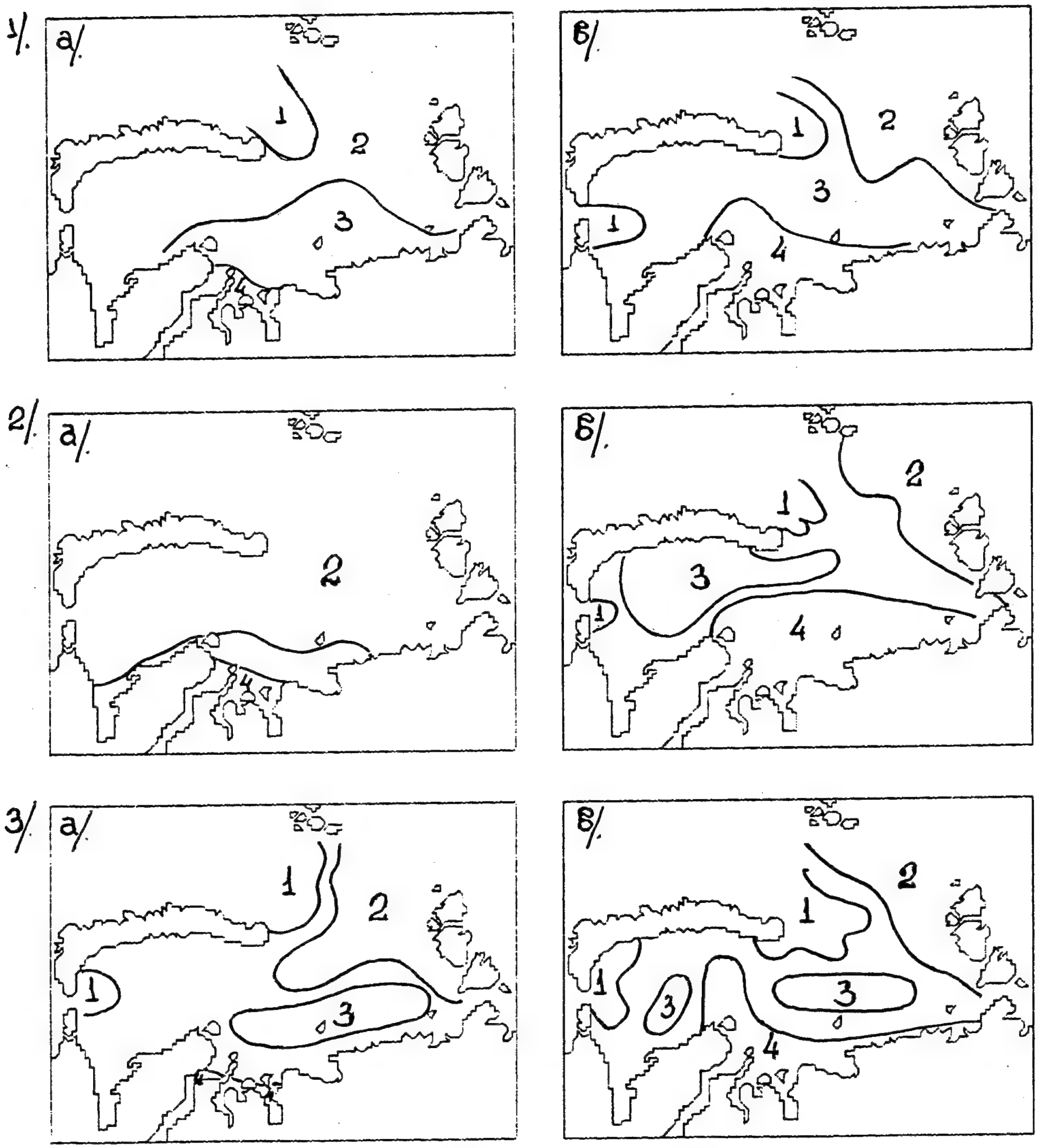


Fig.1.10. Distribution of water masses in the surface layer in winter (a) and in summer (b) : tipical (1), in the years of the prevailing effect of the Arctic maximum (2) and Icelandic minimum (3). Water masses: 1 - water of the Barents Sea, 2 - surface water of the Arctic ocean, 3 - surface water of the Kara Sea, 4 - river water.

[Nikiforov, Shpaikher 1980]

balance and air temperature and the heat advection from the adjacent seas and rivers, under the effect of which there is water heating from the ice formation temperature, characteristic of the winter period, to relatively high water temperatures, observed in August-September.

In the warmer part of the year solar heat is lost first of all due to ice melt, that is why water temperature at the surface practically does not differ from the winter one. Only in the southern part of the sea, which becomes ice free earlier and which experiences the effect of the continental run-off the surface water temperature gradually increases. In summer during the warmest months the water over the ice free area is heated on an average up to 6-8^{0}C (and in some years up to 10-12^{0}C) in the southern sea and up to 2^0 C in the northern part, under the ice the water temperature can rise a little above the freezing point. In winter the water temperature is almost everywhere close to the freezing temperature from the surface to the bottom (-1.5^0- -1.7^{0}C). Only in the troughs of St. Anna and Voronin, by which Atlantic water penetrates the sea, the temperature starts to increase from the level of 50-70 m reaching in the layer of 100-200 m the values of 1.0 - 1.5^{0}C , while deeper it decreases again. In spring the warming over the ice free areas in the south of the sea extends from the surface to the depth. And the water temperature above 0^{0}C is observed down to the level of 15 - 18 m in the south-western part and down to the level of 10 -12 m in the south-east. Deeper it sharply decreases to the bottom. Among ice of the northern part of the sea the winter water temperature distribution by vertical is preserved.

In the most warm months the water temperature in shallow areas in the south-western part of the sea becomes above 0^{0}C from the surface to the bottom. In western areas a comparatively high temperature is observed down to 60-70 m, then it gently decreases with depth. In the east of the sea the temperature from quite high values at the surface (up to 2^0 C) rapidly decreases with depth, reaching -1.2^0 C at a 10 m level and up to -1.5^{0}C near the bottom. In the ice-covered northern sea the vertical temperature distribution in summer is the same as in winter. Thus, the thermocline is formed in summer over the entire territory of the

Kara Sea, free of ice.

At the beginning of the fall cooling the water tenperature at the surface is a little lower than at subsurface levels (up to 12-15 m in the south-west and up to 10-12 m in the south-east). The fall cooling rapidly eliminates the summer heating and makes the temperature equal in the entire water column [*Soviet Arctic 1970; Shpaikher, Fedorova 1977*].

Figure 1.11.a gives a characteristic water temperature distribution at the Kara Sea surface. During the hydrological surveys the temperature field, as a rule, significantly differs from the characteristic one, due to a temporal variability of the heat balance components and dynamic factors (Fig.1.11.b). Figure 1.12 presents vertical water temperature profiles in summer in different parts of the sea.

The salinity distribution in the Kara Sea is governed, mainly, by the characteristics of the water masses and water dynamics. The water inflow from the Barents Sea enhances the salinity in the Novozemel'sky straits, south-western and north-western sea parts. The inflow of Atlantic water is also pronounced in a relatively high water salinity of the northern Kara Sea with the variations in the transports of Atlantic water at the transect between the Spitsbergen and Greenland affecting the water salinity in the northern Kara Sea in two years.

The main feature in the distribution of water salinity appears to be its considerable elevation from the east and south-east from the shores of Yamal to the west of Novaya Zemlya Island from several per mil to more than 33 $^0/_{00}$. In all regions of the sea the seasonal variability of water salinity is well pronounced, being caused by the processes of ice formation and melting and the river run-off variations. In winter the river run-off decreases and simultaneously water salination occurs due to ice formation. The salinity in the upper layer, where the convection takes place, increases everywhere and in the south-western sea, with the exception of the areas, directly adjacent to the river mouths it is 25-30 $^0/_{00}$, being 33-34 $^0/_{00}$ in the northern part and off the Novaya Zemlya island. A comparison of the observation data at the beginning and end of

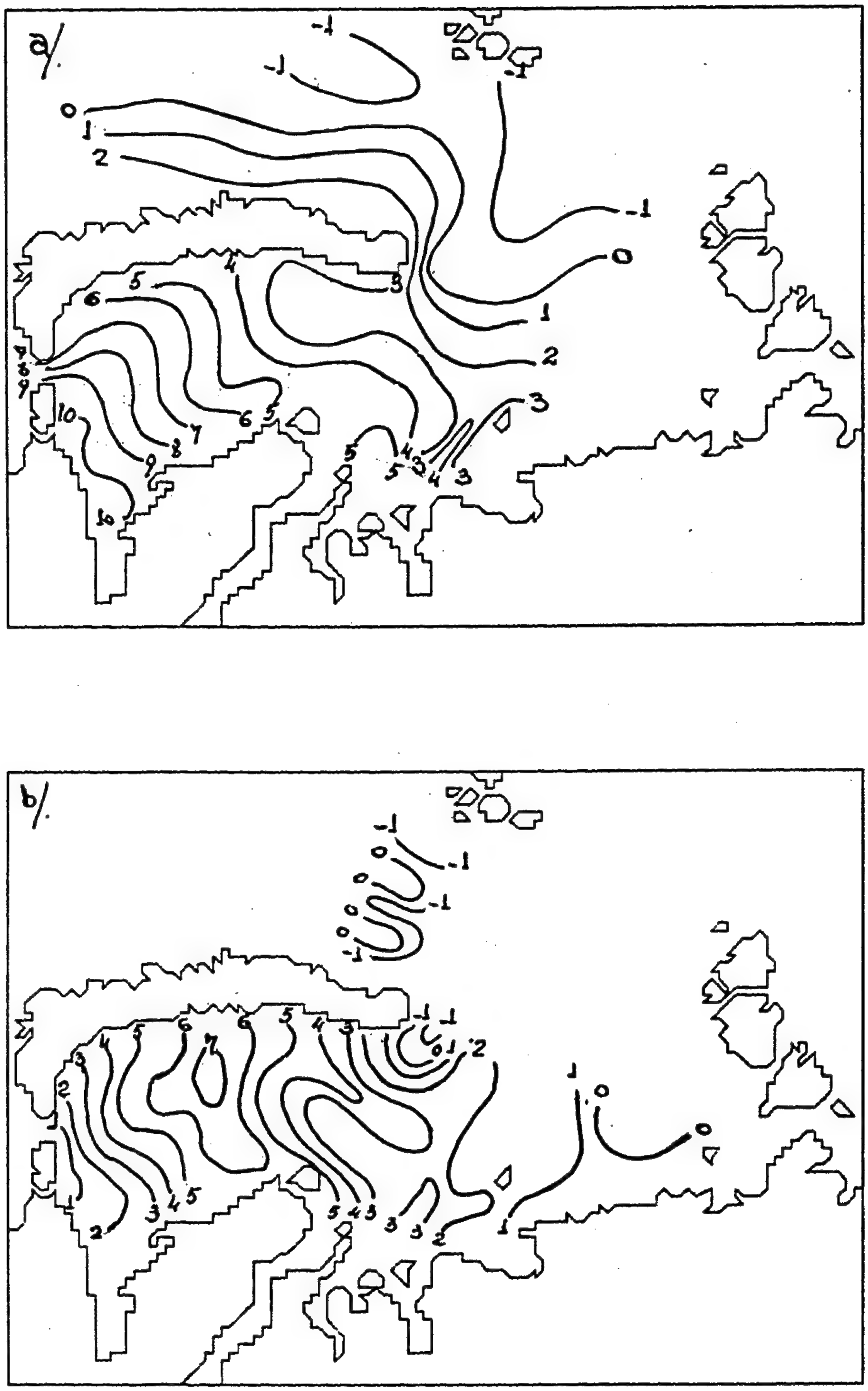


Fig.1.11. Distributions of the water temperature at the surface in summer in different years.
[Dobrovol'skiy, Zalogin 1982]

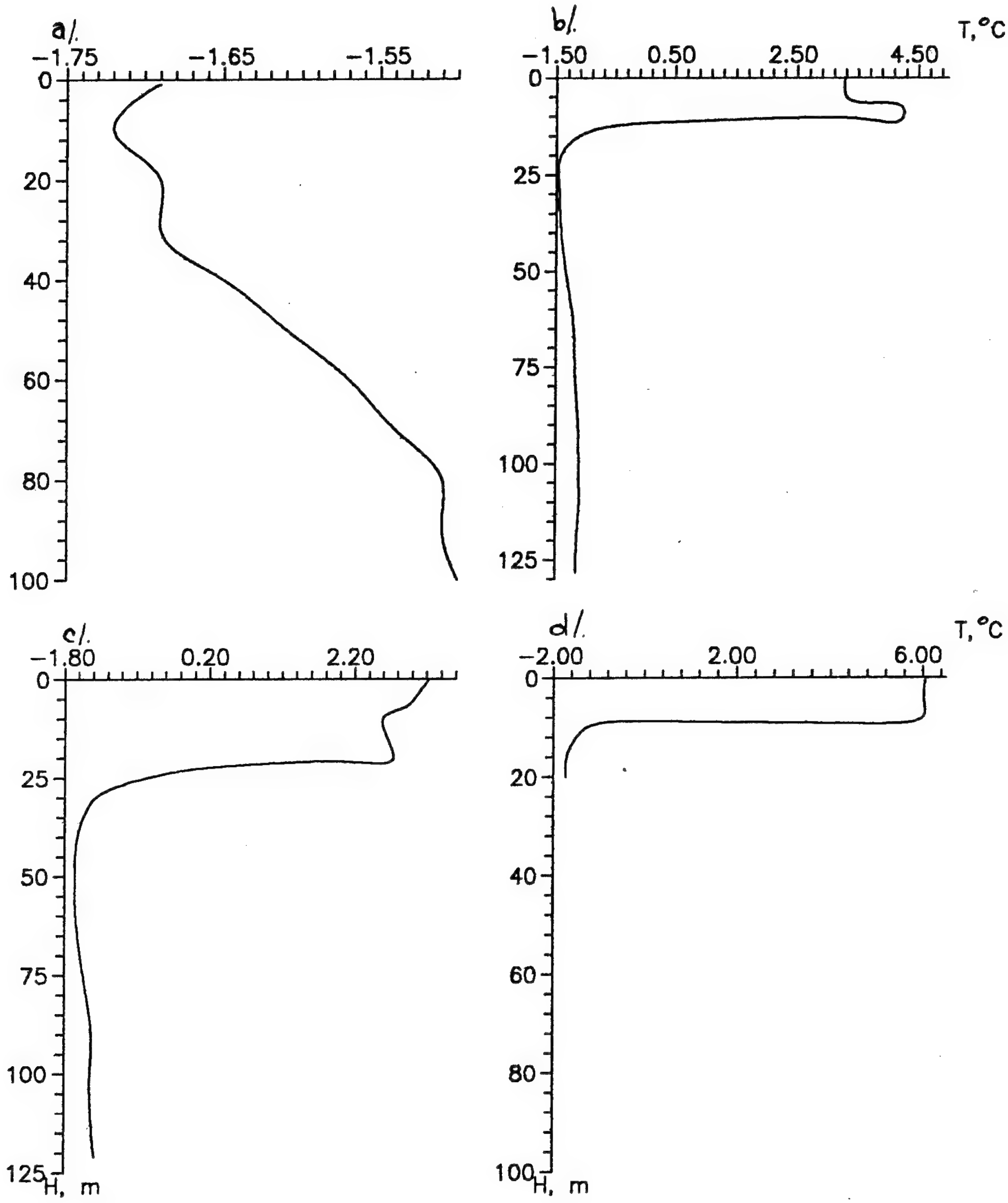


Fig.1.12. Vertical water temperature profiles in summer in different parts of the Kara Sea.

a - northern part; b - central part; c - south-western part; d - southern part.

winter has shown that in the zone of the influence of the continental run-off the value of the salinity increase can reach 5-6 $^0/_{00}$, and outside it - 1 - 2 $^0/_{00}$.

In the warmer seasons the spring inflow of river water reduces the surface salinity in the near mouth areas and in the coastal band. Further, the ice melt and a maximum extent of river water in summer desalinate the surface layer. The lowest salinity (5-10 $^0/_{00}$) is observed in the regions of the mouths of Ob' and Yenisey. Northward of the Ob'Yenisey shallow water area the salinity of surface water increases up to 15-20 $^0/_{00}$. The south-western sea has the same salinity. For the northern regions of the Kara Sea northward and to the north-east of the Zhelaniya Cape the salinity of the surface layers is characterized by a rapid increase from south to north. In the northern regions the highest salinity values are noted (33.8 - 34.0 $^0/_{00}$).

Such salinity distribution is changed by the ice melt. Among floating ice one can observe the salinity at water surface by 7-8 $^0/_{00}$ lower than in the sea areas free of ice. This results in the formation of well-pronounced frontal zones with the salinity gradients up to 1 - 1.5 $^0/_{00}$/km in the areas of the melting ice edge.

The salinity in the water column increases from the surface to the bottom. In winter it increases relatively uniformly over most of the sea from 30 $^0/_{00}$ at the surface to 35 $^0/_{00}$ at the bottom. Near the river mouths the transition from less saline surface water to saline underlying water is pronounced more sharply.

In spring, particularly, at the beginning of the season the salinity distribution is similar to the winter one. Only near the shores the enhanced inflow of continental water desalinates the most upper sea layer.

In summer the salinity from low values at the surface (10-20 $^0/_{00}$) dramatically increases with depth (up to 29-30 $^0/_{00}$) at the levels of 10-15 m, forming a strong halocline. Then it increases more smoothly reaching 34-35 $^0/_{00}$ near the bottom. Such salinity distribution by vertical is particularly well pronounced in the southern sea part - in the zone of the influence of the continental run-off and in the northern areas among drifting ice

[*Soviet Arctic 1970; Stepanov 1972*].

In accordance with a different stratification the conditions created are unequal for the development of a wind-driven mixing in different sea regions. In the central and western sea regions the mixing penetrates down to the level of 10-15 m, at the sea side of the mouths of Ob' and Yenisey - up to 5-7 m.

The fall-winter convection is much more developed. The most favourable conditions for the density mixing are created near the shores of Novaya Zemlya, where there is observed a sufficiently weak water stratification, rapid cooling and a strong ice formation. The convection here penetrates the depths of 50-70 m. The same conditions for the convection development and approximately similar depths are observed in the south-western and north-western regions. In the cenral regions and at the Ob'Yenisey mouth sea side the density stratification makes the convection difficult, which develops mainly due to the salination during ice formation, reaching the bottom only in late winter.

Figure 1.13 shows two fields of water salinity distribution at the Kara Sea surface varying significantly due to the difference of the dynamic factors during the surveys.

Also shown are the diagrams of the vertical water salinity distribution in various sea parts in summer (Fig. 1.14).

One of the main factors for the southern Kara Sea, which forms the thermohaline and hydrochemical regime, appears to be the presence in the surface layer of a strongly desalinated water of the continental run-off, which extends over the area up to 20% (and from some estimates up to 1/3) of the Kara Sea region. The ratio between the annual volume of the river run-off to the sea and the sea volume proper is about 0.01.

The effect of the river run-off is particularly evident during the spring-summer period, as the near mouth sea area due to the water outflow and its heat rapidly becomes ice free, which contributes to the radiation water heating. The stratification of water, which occurs in the summertime due to a combined influence of the river run-off and the ice melt, prevents the water heating spreading into the layers, located below the pycnocline.

With the onset of water cooling in the fall the presence of

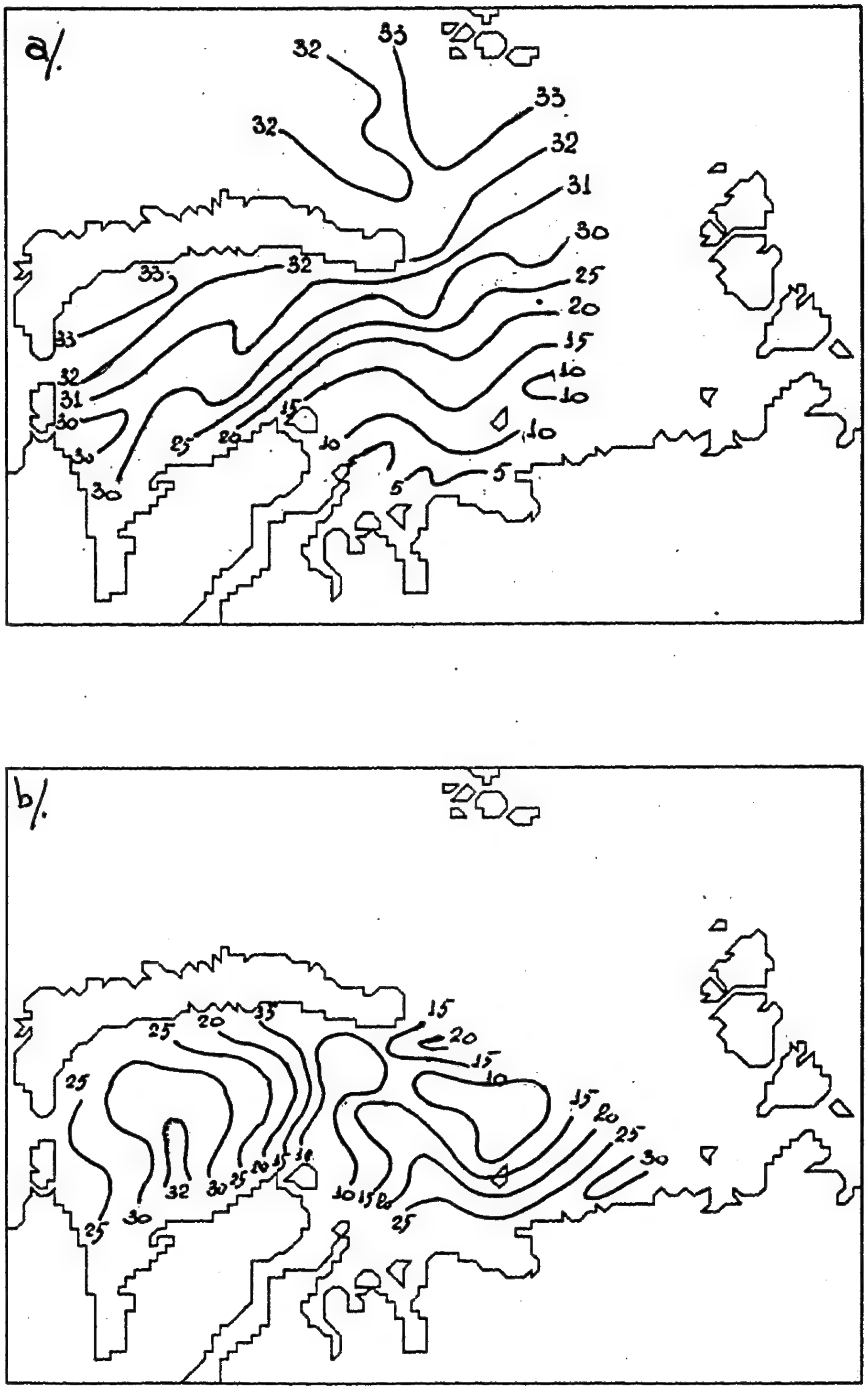


Fig.1.13. Distributions of the water salinity at the surface in summer in different years.
[Dobrovol'skiy, Zalogin 1982]

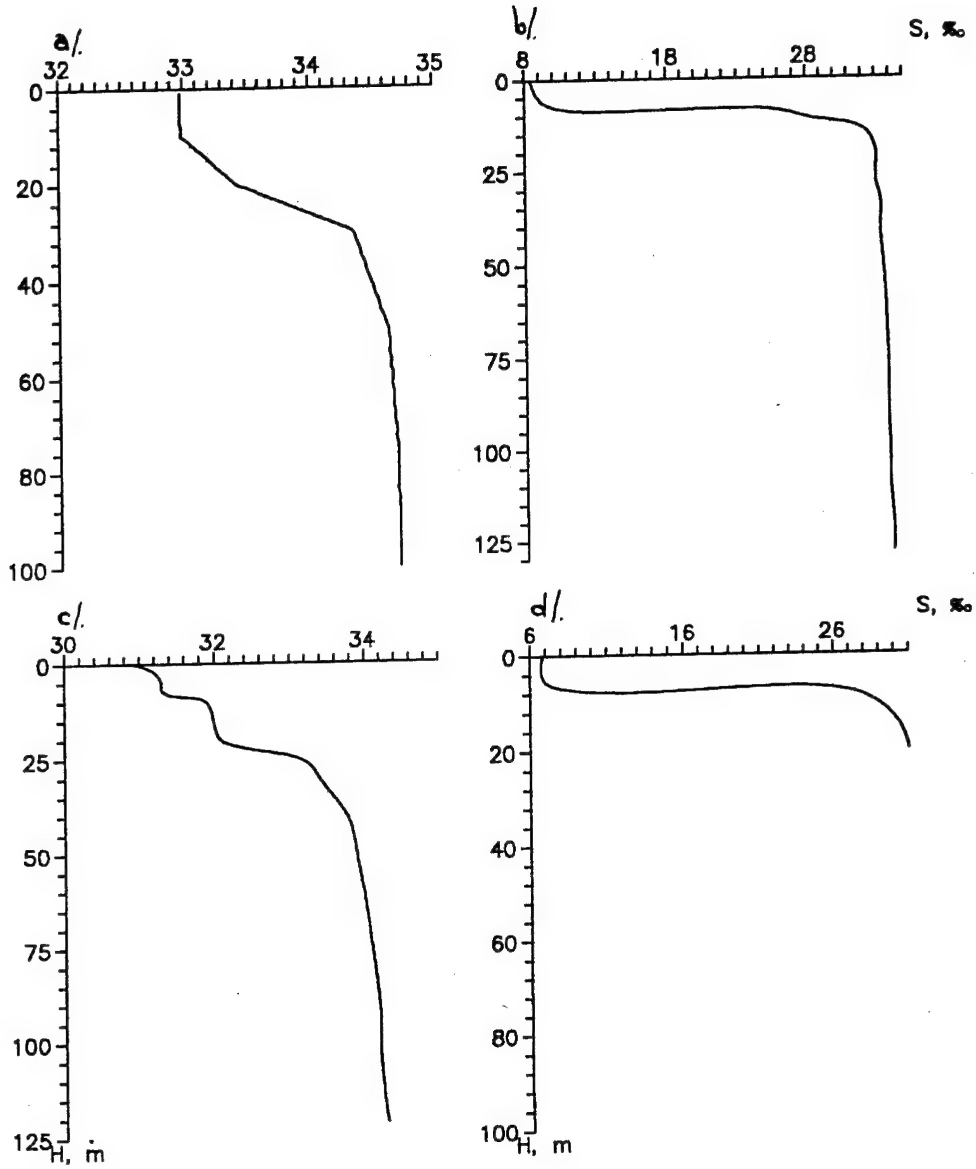


Fig.1.14. Vertical water salinity profiles in summer in different parts of the Kara Sea.

a - northern part; b - central part; c - south-western part; d - southern part.

the density stratification complicates the heat exchange between the surface and lower waters, thus resulting in a more rapid ice formation.

Usually three types of the continental water extent are delineated: western, fan-shaped and eastern (Fig. 1.15). With the western type the desalinated water can occupy the area up to the latitude of the Zhelaniya Cape [*Antonov 1964; Soviet Arctic 1970*]. A large effect on the extent type is produced by the dominating pressure formations in the wintertime and the total water run-off of a given year. The presented subdivision into types is quite arbitrary.

The zone of river and sea water interaction occupies an area, restricted by the water salinity values from 1 $^0/_{00}$ near bottom up to 25 $^0/_{00}$ at sea surface. The warm and fresh river water flows onto a more dense sea water, forming a tilted hydrofront with exceptionally large vertical and horizontal salinity gradients, and, hence, density. Vertical water salinity gradients can reach 10 $^0/_{00}$ / m and horizontal - up to 1-2 $^0/_{00}$ / km. The water temperature gradients are quite well pronounced, but the spatial temperature distribution is more smoothed in connection with the region being shallow and the radiation water warming. That is why to follow the waters of the continental run-off by the temperature distribution is rather difficult. One notes the existence of a well-pronounced hydrofront, which has a complicated character (doubling, ring formation). There is also a significant interannual, seasonal and intraseasonal variability of spatial distribution of desalinated water and the hydrofront position.

In addition to the processes, inherent to all frontal zones, the Kara Sea has specific features, which are related with the high-latitudinal position of the sea - the existence of the ice cover and a sharp reduction of the river run-off in winter. Also, a significant influence is produced due to the sea being shallow.

Small depths contribute to the generation of non-linear internal waves, destruction and transformation of internal waves coming from deeper sea regions. The values of internal waves over shallow zones reach 0.5 of the sea depth [*Stanovoy 1984*]. Such waves are, as a rule, unstable and their decay induces unstable

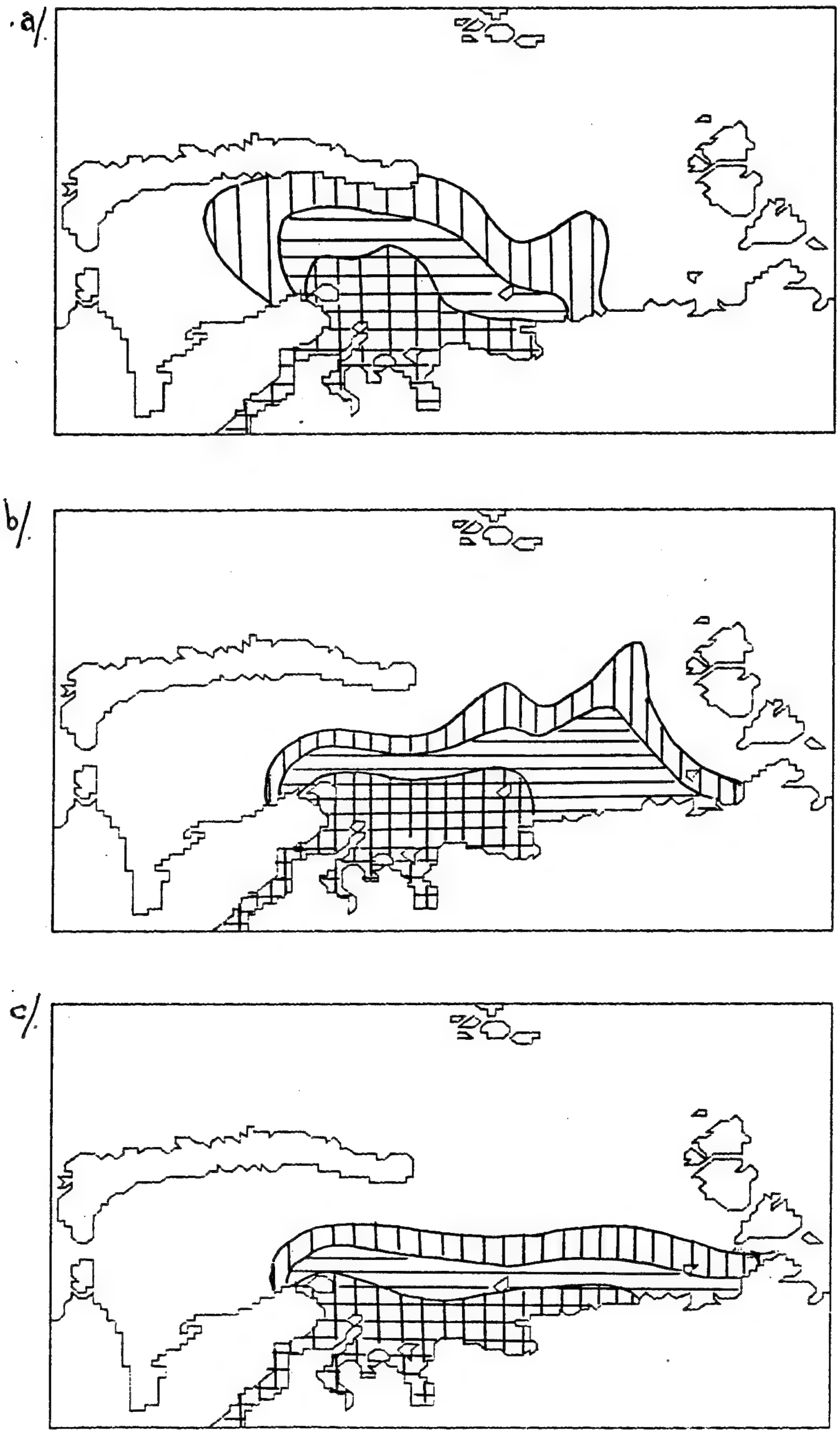


Fig.1.15. Types of river water extensions

a - western; b - fanshaped; c - eastern.

(||||||) - 70 - 50 %; (≡) - 90 - 70 % : (#) - more then 90 %.

[Soviet Arctic 1970]

stratification. The ice cover affects the internal waves when the pycnocline is located sufficiently close to the bottom ice surface. And a combination of the ice cover and small depths contributes to the formation of non-linear internal waves. There are also cases of soliton appearance (Fig. 1.16).

During the passage of the spring flood waves, that is, during the maximum transports of river water (June, July), a strong water desalination and warming in the Ob' Gulf, Yenisey and Pyasina Bays and in the coastal regions of the Kara Sea takes place (regretfully no observations during this period were made). During the decrease of the flood and transition to the summer low water a relative stabilization of the position of the interaction zone occurs, depending on the total river run-off, location of the water masses of the Kara Sea and atmospheric processes, prevailing over the sea. A background thermohaline structure is being formed. The southern boundary of the interaction zone is in the northern parts of the Ob' Gulf, Yenisey and Pyasina Bays, while the northern boundary can reach latitude of the Zhelaniya Cape, where surface water, desalinated by the continental run-off joins the desalinated water near the ice edge.

The thermohaline water structure in the interaction zone has both a strong interannual and interseasonal variability. In August-September there is a decrease of the river run-off and all changes of the thermohaline structure occur under the influence of atmospheric and dynamic factors. It is necessary to note that the expedition studies in the Kara Sea are carried out exactly in August-September and the obtained salinity fields correlate quite weakly, as a rule, with the background structure.

Fig. 1.17 shows a vertical water salinity distribution at a latitudinal transect northward of the Ob' Gulf, obtained in different years and different months. The salinity change in the surface layer and the change in the thickness and depth of the pycnocline are well seen.

Thus, the zone of the interaction of the continental run-off and sea water in the summer-fall period does not have any clear boundaries and the area, restricted by the isohaline 25 $^{0}/_{00}$ constantly changes in time and space.

In winter the run-off dramatically decreases, saline water

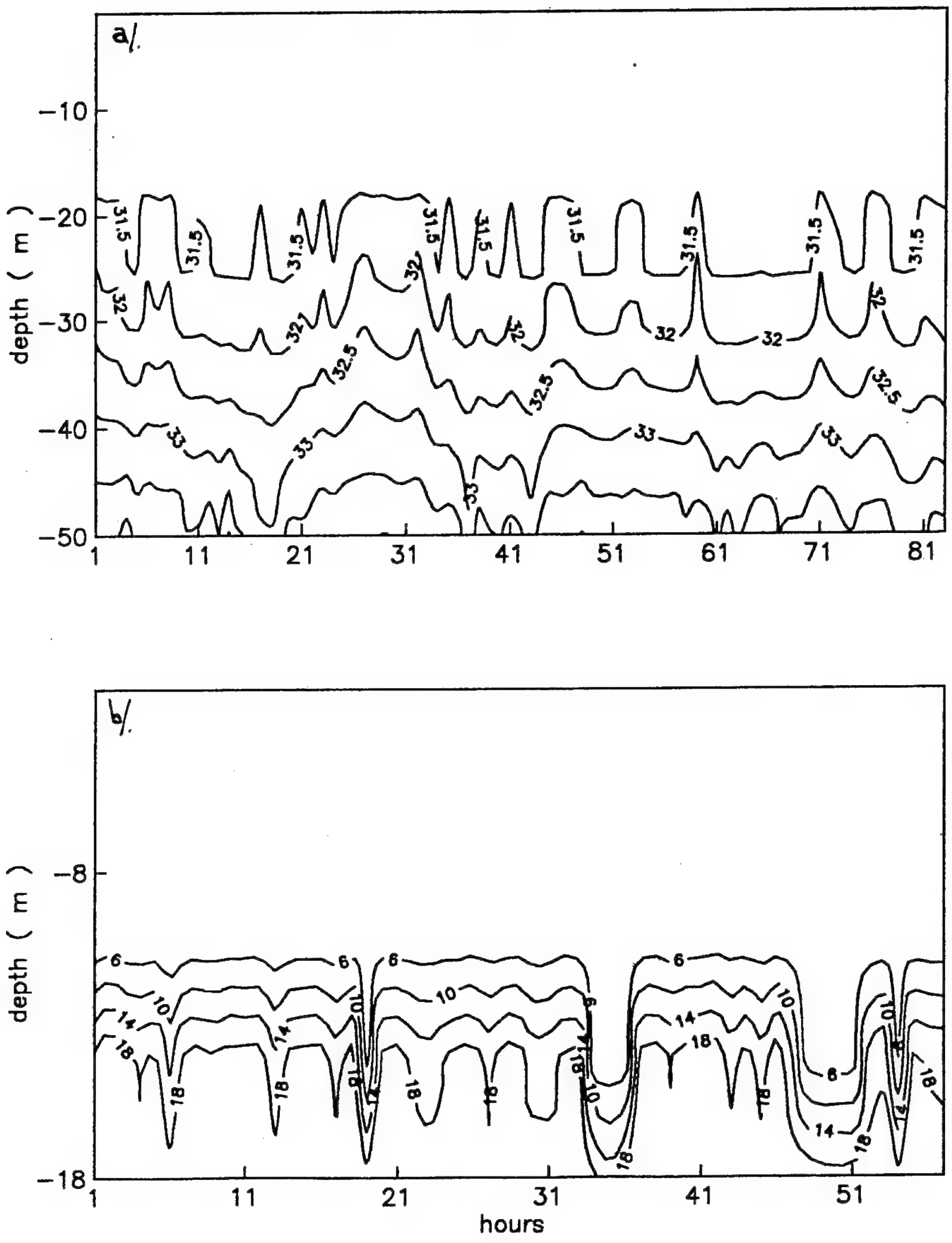


Fig.1.16. Internal waves in the central part of the Kara Sea in summer (a) and in the southern part of the Sea in winter under the ice cover (b)

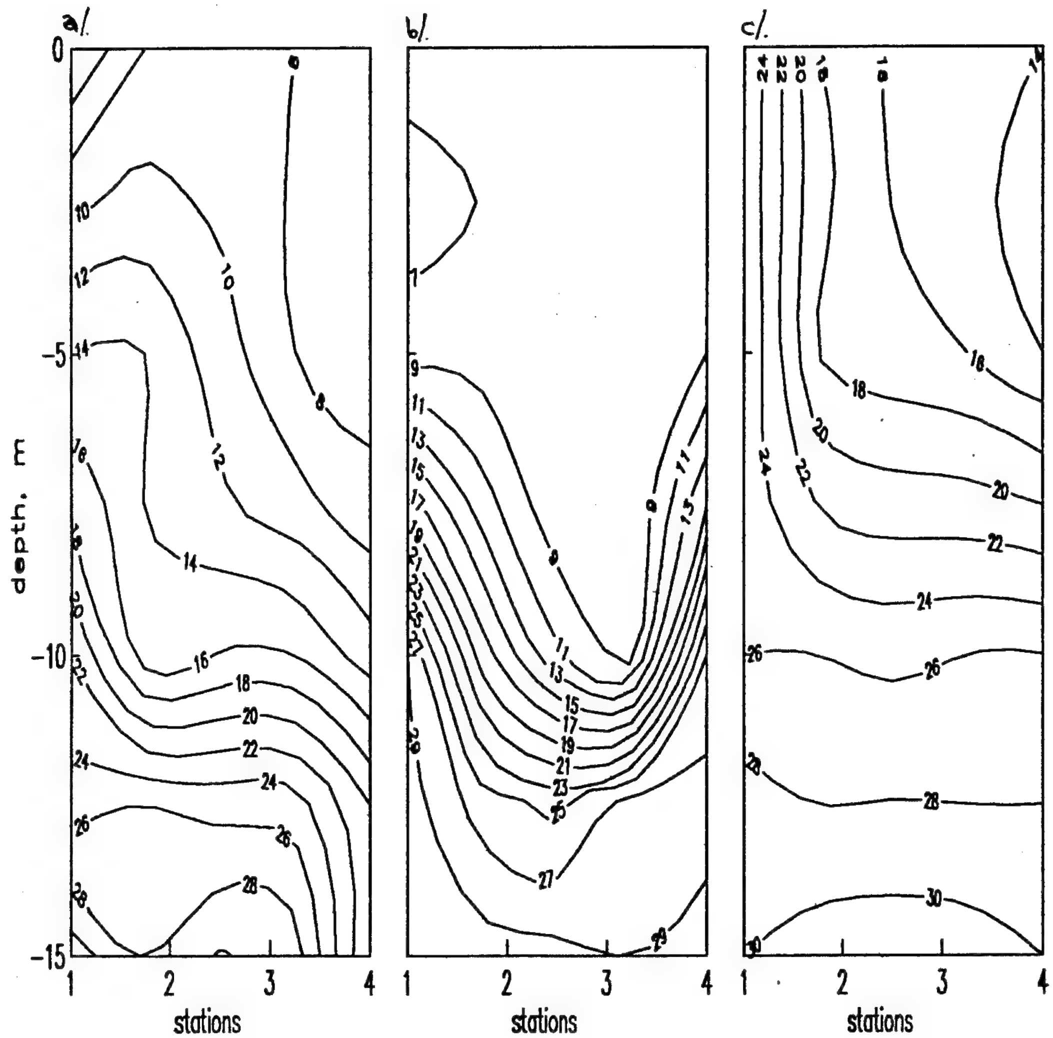


Fig.1.17. Vertical water salinity distribution at a latitudinal transect northward of the OB' Gulf (a - IX,1972; b - YIII,1977; c - IX,1977)

penetrates the river mouth areas (thus, in the Ob' Gulf the water with a salinity of 1 $^0/_{00}$ at the near-bottom level reaches in some years almost the Taz Gulf). In the north of the Ob' Gulf and Yenisey Bay the salinity in the surface layers is observed to be up to 25 $^0/_{00}$. Practically in all mouth areas one observes the isothermal conditions, that is in winter the hydrofront is not distinct, the vertical and horizontal salinity (and density) gradients decrease.

Thus, in winter the zone of interaction of the continental run-off and sea water is limited by the river mouth areas and by the mouth coasts of the Kara Sea.

1.5. Hydrochemical regime of the Kara Sea

The group of major biohydrochemical parameters of sea water usually includes dissolved oxygen, both in the absolute form of expression (ml/l, mg-a/l), and in the relative form (% of saturation), as well as concentrations of mineral forms of nutrients (phosphates, nitrites, nitrates and silicates). This is a minimal set of parameters, which allows one to estimate the direction of biological processes in sea water, since mineral nutrients are considered to be the basis of primary productivity, and the existence of all subsequent links of the trophic chain depends on whether their concentrations are within the optimal limits for the life of phytoplankton. The importance of dissolved oxygen for the life of sea inhabitants is well known [*Alekin, Lyakhin 1984; Privol'nev 1948; Yudanov 1929*]. In addition, the Arctic Seas during a short polar summer appear to be a significant source of oxygen to the atmosphere due to the oxygen release during photosynthesis [*Lyakhin, Rusanov 1980; 1983*].

Hydrochemical parameters appear to be good indicators of water masses, conditions of their formation and dynamics, that is why they are widely used to address oceanographic problems.

It should be noted that a complex of biohydrochemical parameters of sea water is much wider. It includes carbonate components and nutrients in the organic form, both in the dissolved and suspended state, as well as total concentrations of nutrients. However, due to the time-consuming methods of the

analysis, these parameters of sea water were rarely determined in the Arctic Seas. The obtained data require to be specified and their amount is inadequate for a justified inference of the typical features of spatial-temporal variability.

The oxygen, dissolved in sea water, was determined in the AARI expeditions by means of the Vinkler's method with the accuracy of 0.02 ml/l. The solubility of oxygen was calculated from International Tables [*Tables of oxygen solubility in sea water 1976*].

The content of silicates, phosphates, nitrites and nitrates in sea water was determined by colorimetry methods according to the Handbook [*A Handbook on the methods of sea water chemical analysis 1977*]. The accuracy of determining these parameters is 10-15% depending on concentration, the sensitivity of the method for the silicate analysis - 0.3 μMol/l, nitrites, nitrates and phosphates - 0.05 μMol/l. During the cruises of the R/V the "Akademik Shuleikin" and "Professor Mul'tanovsky" silicates, nitrites and nitrates were determined by means of AKEA self-analyzer with an accuracy of 4-7%.

The observation coverage with regard to different seas and their regions is not equal. The largest number of stations are occupied in the south-western and central Kara Sea and in the eastern Laptev. The observations in the summertime were carried out very rarely in the East-Siberian Sea and in the north-eastern Kara Sea. In these regions winter observations prevail. The hydrochemical conditions during the ice cover formation and decay in early spring remain to be inadequately studied.

The hydrochemical observations for the period up to 1975 are summarized in Rusanov et al. [*Rusanov.et al. 1979*]. The present overview gives the description of the distribution of hydrochemical parameters using this monograph, the Arctic Ocean Atlas and other sources [*Antonov 1957; Belyakov, Rusanov 1971; Berezin 1985; Buynevich et al. 1980; Vasilyev 1976; Viese 1943; Guryanova, Musina 1960; Ivanov et al. 1984; Kazeyeva 1960; Lyakhin, Rusanov 1980; Lyakhin, Rusanov 1983; Mosevich 1947; Musina, Belysheva 1960; Petrov 1928; Privol'nev 1948; Rusanov, Vasilyev 1976; Rusanov et al. 1979; Sidorov, Gukov 1992; Smagin et al. 1980; Smirnov 1955; Ysachev 1968; Shirshov 1937;*

Shpaikher, Rusanov 1972; Ecology and biological resources of the Kara Sea 1989; Yudanov 1929]

The river run-off, which produces a complex impact on the hydrochemical structure, is considered to be of primary importance for the Kara Sea. The ice cover presence much of the year is one of the most significant factors, as well as ice melting and formation processes.

By the distribution of hydrochemical parameters in the surface layer the Kara Sea is quite clearly divided into three parts : central, south-western and northern.

According to the data, obtained during the navigation period (August-October), maximum values of dissolved oxygen at a 0 m level were usually observed in the marginal zone of drifting ice - up to 1.30 mg-a/l. On the one hand, this is attributed to the lowest water temperature and freshening of the surface layer due to the ice melt - these both factors increase the oxygen solubility in sea water, on the other hand, unique conditions are created in the marginal zone for the development of phytoplankton and water saturation by oxygen due to photosynthesis.

High oxygen values (0.80-0.85 mg-a/l) were observed in the sea regions, which are subjected to the influence of the river run-off, north of the Beliy island at latitude $74^{0}30'$N (the Ob' river effect) and north of Yenisey Bay (the Yenisey river effect). However, in spite of high values in the absolute expression, the surface layer in the regions of the river outflow is, as a rule, saturated with oxygen up to 100%, and the deficit can reach 5%. This is attributed not only to the input of a large quantity of organic substances with river water, on which oxidation the dissolved oxygen is used, but also to the river water cooling with its progress northward. A constant water temperature decrease provides for the increase of the oxygen solubility, and its supply from the atmosphere can be not quick enough to follow the temperature changes, which is especially typical of the middle of the summer period, when some drop in the photosynthesis activity of phytoplankton is observed.

In the south-western Kara Sea, which is not subjected to the effect of the river run-off, in the absence of drifting ice usually a uniform distribution of dissloved oxygen is observed

within the range 0.60 to 0.70 mg-a/l. In the event when a well heated and more saline Barents water inflows in large volumes through Kara Gate strait, the lowest oxygen values (0.58-0.62 mg-a/l) are recorded in the southern sea regions. Minimum oxygen values in the summertime were observed in the Baidaratskaya Gulf due to a good heating of the surface layer and in the southern regions of the Ob' Gulf and Yenisey Bay.

The surface layer in the northern Kara Sea, formed under the effect of the Barents Sea and Arctic water masses, as well as of ice melting is characterized by a large oxygen supply within 0.70 to 0.80 mg-a/l and saturation more than 100%. And the maximum values are observed near the ice edge, and the minimum ones (0.68-0.76 mg-a/l) - off the northern tip of the Novaya Zemlya island in the water flow from the Barents Sea.

Mean distribution of the dissolved oxygen in the surface water of the Kara Sea for the observation period is presented in Fig.1.18. Special conditions for water saturation by oxygen are created near the ice edge, in the frontal zones, in the Ob' and Baidaratskaya Gulfs, in Yenisey, Gydan'sky and Pyasinsky Bays.

The change of the dissolved oxygen concentration with depth is various sea parts is mainly governed by the water mass alternation by vertical and its loss due to the oxidation of the organic substance. In the central part of the sea at small depths there are observed the largest gradients of oxygen concentration up to 0.04 mg-a/l per meter. The concentration varies from 0.76-0.90 mg-a/l at the surface to 0.45-0.55 mg-a/l at a 15-20 m depth. Such distribution is typical of the southern regions of the central sea, which is indicated by the observation results at the transect Beliy island - Dikson island. In this region the surface layer, freshened by the river run-off overlaps the layer of cold (-1.0^0 - -1.5^0 C) and salty water ($30\text{-}33^0/_{00}$) during the whole year. Large density gradients prevent the gas exchange between the layers. At the condition of the rivers exporting a large quantity of organic substance, to oxidize which oxygen is lost, a considerable deficit of the dissolved oxygen appears in the lower layer (57-65%). The thickness of the layer of stagnant, poorly ventilated water in the eastern part of the transect reaches 20 meters at depths from 30 to 35 m. Stagnant water is

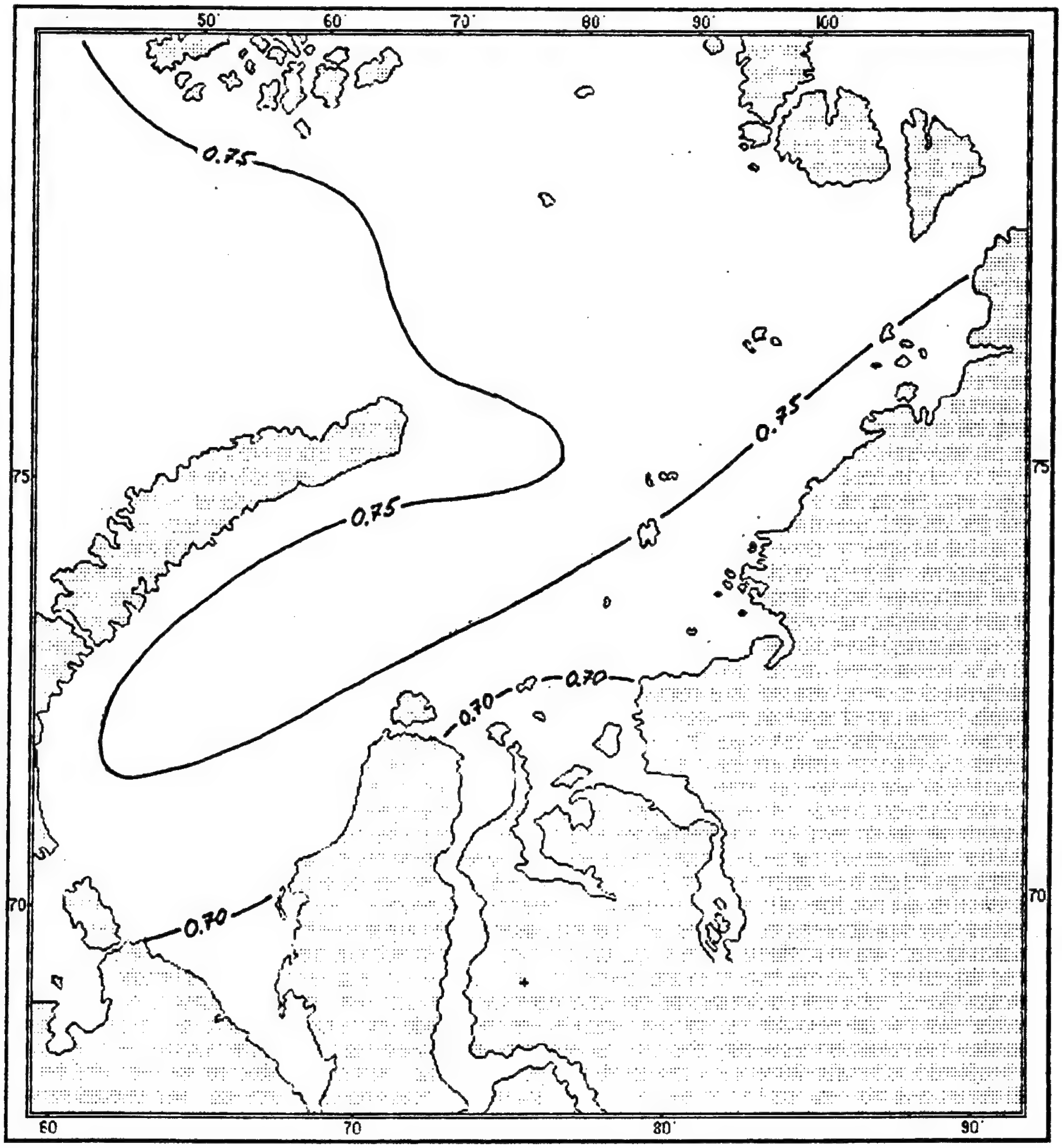


Fig.1.18. Mean distribution of the dissolved oxygen (mg-a/l) for the observation period in the surface water of the Kara Sea [Rusanov et al. 1979]

observed at the near-bottom levels in the northern Ob' Gulf and the adjacent regions. Flowing northward, the waters with a large oxygen deficit, disturb the vertical hydrochemical structure, which is evident in the existence of the layers with a minimum oxygen content at the levels, occupied by downflowing water according to its density.

At depths less than 15 m in summer usually a uniform water layer is observed from the surface to the bottom, formed as a result of intensive mixing. A uniform distribution of oxygen and other hydrochemical parameters is observed in the Ob' Gulf and Yenisey Bay south of the hydrological fronts, as well as in the shallow Baidaratskaya Gulf.

In the south-western sea vertical oxygen distribution is characterized by the existence of a concentration maximum (in absolute values and in percent saturation), which locates at 10-15 m depths. The formation mechanism of this maximum can be explained as follows. Spring processes of the phytoplankton development, obviously, begin in the surface sea layer prior to an intensive ice melt. As a result of the photosynthesis, the saturation of water with oxygen takes place, to which low, negative water temperature contributes, and a layer supersaturated by dissolved oxygen up to 110-120%, forms. Further, this layer is overlapped by a more fresh and less salty water, formed partly due to the ice melt and freshening by the river run-off. At a 5-10 m depth a transient layer is formed with large density gradients, preventing mixing of the layers and gaseous exchange between them. A gradual heating of the upper layer leads to a decreased oxygen concentration in it, and the lower layer remains "conserved", the oxygen content in it changing little.

In the northern regions of the south-western sea off the frontal zone at a 25-35 m depth there is a minimum of dissolved oxygen concentration, governed by the spreading of water, which lost a large amount of oxygen in the near-bottom layers in the central sea. Oxygen minima can be observed in the lower parts of transient layers, but they are related with the accumulation of detritium in these layers, to oxidize which the dissolved oxygen is lost.

At the depths from 40 to 70 m in the south-western sea there is a layer of well aerated water (0.67-0.72 mg-a/l) of winter formation with a very low temperature (-1.8^{0} - -1.9^{0}C). In the deepest regions of this sea (Novozemel'sky trough, etc.) a gradual decrease of oxygen concentration from the 50 m level to the bottom takes place at a comparatively high percent of saturation (more than 70%). Only near the very bottom in the Novozemel'sky trough at a depth of more than 300 m and in the bottom depressions, small by size, in the central regions of the south-western sea there were observed low oxygen values (less than 0.55 mg-a/l, less than 70% saturation), which indicates an insufficient ventilation of the near-bottom levels in these regions.

In the northern sea region, particularly in the regions, bordering the Barents Sea, the presence of the layer of the minimum of dissolved oxygen, is related with the income of warmer and saltier Barents Sea water.

A complex multiyear distribution of oxygen concentration is typical of the deep Anna and Voronin troughs, where at the border with the Arctic Basin different water masses of local origin - Arctic, Atlantic and Barents Sea waters interact.

The frontal zones in the Ob' Gulf and Yenisey Bay are considered to be the main source of silicates in the Kara Sea in the summertime. Maximum concentration of silicon in the zone of hydrofront in the Ob' Gulf usually exceeds 150 µMol/l, in Yenisey Bay the silicon values are two-three times less.

Freshened water spreads northward, forming in the central sea region a surface 5-10 m water layer with large horizontal salinity gradients and silicate concentration (Fig.1.19). Actually, the entire central sea region presents an extensive frontal zone with the system of very variable hydrological fronts, located in different directions. The position of the 250 µgSi/l isoline (or, approximately, 10 µMol/l) is assumed to be the boundary of the influence of the river run-off, as well as the boundary of the central sea region. This value has been chosen taking into account the data for wintertime, because as a result of winter convection the silicon concentration in the surface layer can increase up to 7.0-7.5 µMol/l, especially in

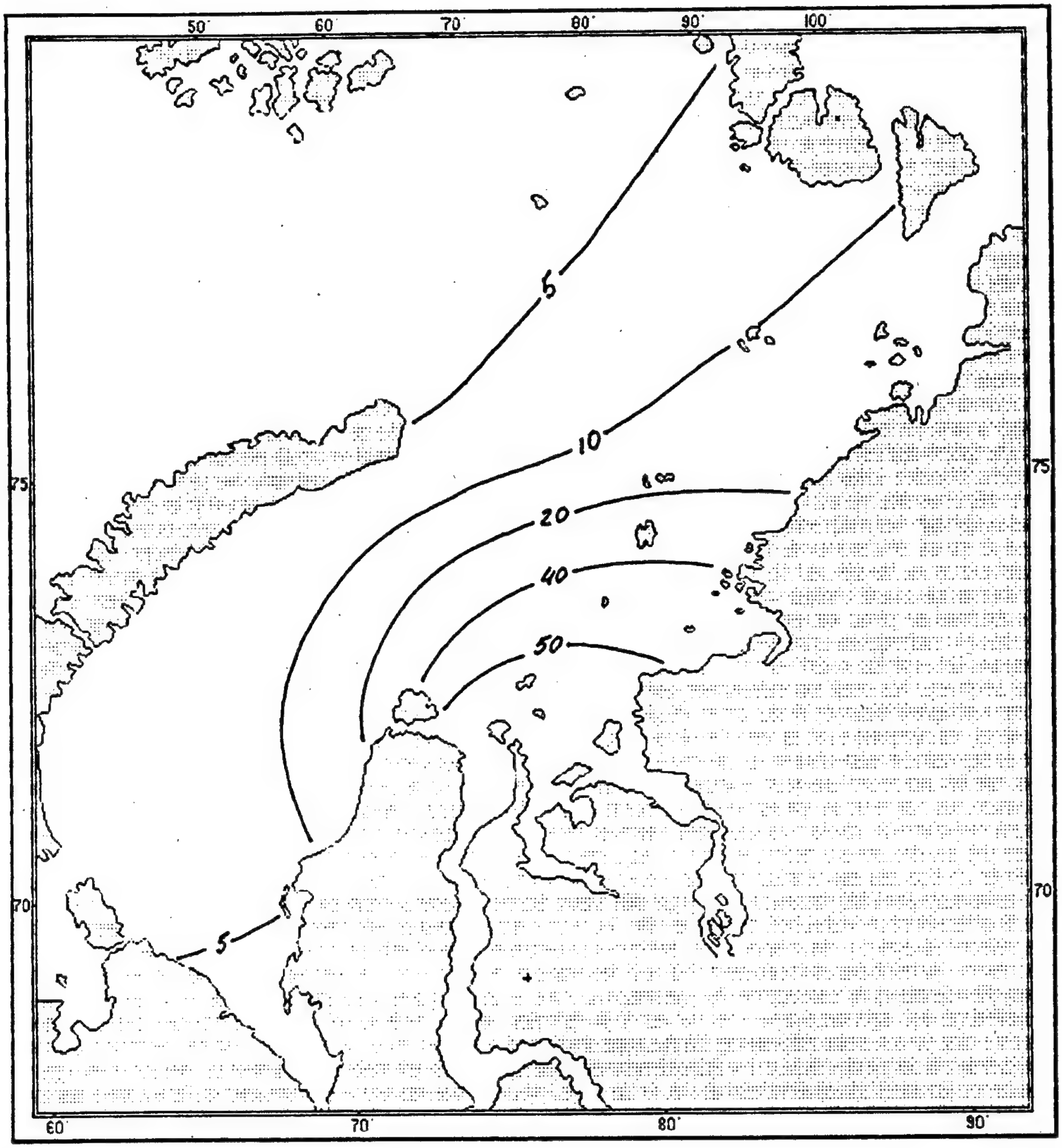


Fig.1.19. Mean distribution of the silicate concentration (µMol/l) for the observation period in the surface water of the Kara Sea [Rusanov et al. 1979]

the regions of the effect of the Barents sea water mass.

The surface water layer in the south-western and northern sea in summer is characterized by minimum concentrations of silicon, less than 3 μMol/l. Often the silicon content decreases up to the sensitivity of the analysis method (0.3 μMol/l) as a result of the development of diatoms.

Phosphates, nitrites and nitrates in the surface layer of the Kara Sea in summer are contained in very small concentrations over the entire area. At sparse hydrological stations, usually situated off the coast in the areas of intensive vertical water motions and hydrofronts the phosphate concentration exceeds 0.05 μMol/l. At the same stations higher values of nitrates are recorded.

In the regions of sea ice extent practically a complete absence of these nutrients during the bloom of phytoplankton is usually observed.

In the central sea the silicon concentration decreases with depth up to 20-30 μMol/l. The only exception are the areas where the depth is not more than 15 m and the entire water layer can be mixed at storm conditions from the surface to the bottom. In these areas the near-bottom silicon concentration differs little from the silicon values at the surface, reaching 35-40 μMol/l. The layer of the largest gradients of silicon is situated between the levels of 5 and 10 m in the central region of the sea.

In the south-western and northern sea , where the effect of river water is not evident, the silicon concentration increases with depth. Several layers with enhanced gradients are observed. The upper layer is located between 10 and 15 m levels. In this layer the most sharp increase of the concentration of all mineral nutrients occurs. For many regions this is the layer of the concentration maximum of nitrites, their content increasing up to 0.15-020 μMol/l, while in the other layers the concentration of nitrites does not exceed 0.1 μMol/l. The layer of enhanced gradients of silicon concentration at a depth of 150-200 m is well-pronounced.

At the near-bottom levels in the Novozemel'sky trough the silicon concentration reaches the values of 15-20 μMol/l.

In the northern sea the silicon concentration increases with

depth, reaching 7-14 μMol/l near the bottom. The existence of intermediate extreme values in the vertical distribution of silicates is related with the input of near-bottom water from the central sea regions, as well as with alternating layers of the Barents Sea water of winter and summer formation and other water masses.

Over the entire area of the Kara Sea one observes the increase of concentration of phosphates and nitrates with depth, but the gradients in various sea regions are different. The values of these parameters and their ratios at near-bottom levels differ significantly, depending on the formation conditions of bottom water.

In the Arctic Seas during polar day the daily changes of hydrochemical parameters, related with the alternation of dark and light periods are not very much noticeable, as compared with mid-latitudes.

The available data allow an understanding of the amplitude of synoptic variability in different sea regions. Naturally, the largest changes are typical of the frontal zone, where the gradients of hydrochemical parameters (especially silicon) have maximum values. The wind direction influences the location of hydrological fronts, which are governed by the river water outflow, and, hence, the shift of a thin layer of surface water with high concentration of silicates. In the northern sea the wind conditions influence the position of the drifting ice edge and, hence, the distribution of hydrochemical parameters.

In the south-western region of the sea the changes of hydrochemical parameters in connection with synoptic processes in the atmosphere and at sea are less evident, than in the other sea regions, except for the regions, adjacent to the straits, through which the Barents sea water inflows to the Kara Sea. Its spreading is closely connected with the atmospheric processes.

The amplitude of the oxygen concentration variation in the points, where the observations were carried out with 5-7 day interval, was reaching 0.03-0.05 mg-a/l. The concentration of phosphates and nitrites in surface water changed little, since over the entire area there were observed minimum values in the summertime. The changes of the silicon content for the same

period can reach large values - from 30 to 100% of the concentration. In some cases the silicon concentration in the surface layer in the hydrofront area changes by 2-3 times.

One should note such interesting phenomenon in the Kara Sea as coastal upwellings, periodically occurring off the coast of the Novaya Zemlya islands, Yamal peninsula and other regions, affected by the wind, directed along the shore. Vertical motions of sea water result in the decrease of the thickness of the upper quasiuniform layer, decrease of oxygen concentration in it up to 95-98% saturation and increase of concentration of nutrients.

The hydrological surveys were carried out by the expeditions of the AARI from August to November. During this time it was possible to make 2 sea surveys and at some transects the observations were carried out 3 times during the navigation. These data allow some conclusions about seasonal variability of hydrochemical parameters during the navigation period.

In early August the oxygen content in the surface layer is characterized by the largest values, however, one should take into account that there is a data gap in June-July. There is some evidence to suggest that the maximum of concentration in the annual cycle occurs during these very months, being governed by low water temperature, desalination due to ice melt and phytoplankton bloom.

The heating of the surface layer, spreading of river water and attenuation of photosynthesis lead to a decreased oxygen concentration in sea water. The minimum of concentration is usually observed in early September. The amplitude of the changes in oxygen content from early August to mid-September is usually 0.1-0.2 mg-a/l, but it is different for individual sea regions, depending on the spreading of river water, ice and weather conditions.

With the advance of the fall cooling of the surface layer the oxygen concentration in it gradually increases, but this is prevented by the convective and turbulent mixing with the lower water layers, less saturated with oxygen, which is typical of the central sea region. In the south-western sea, where the subsurface layer in the summertime contains large oxygen supply, the oxygen concentration in the surface layer increases at a

greater rate.

In the wintertime the zone of minimum values north of Novaya Zemlya is related with the spreading of the Barents Sea water. In the central sea there is a mixed oxygen distribution in the surface layer: high concentrations in the region of the Beliy island and low values north of Yenisey Bay, which is, probably, related with the river water outflow and with the conditions of the water thickness mixing as a result of thermal convection and during ice formation. For shallow water regions these processes produce a significant effect on the formation of the vertical hydrochemical structure.

Seasonal changes in the concentration of nutrients in the surface layer are most distinct in the surface layer, where the silicon concentration decreases from August to September by 1.5-2 times. The concentration change in the near-bottom layers is 10-20%.

During the summer months the concentration of phosphates and nitrates in the surface sea layer changes little, but with the development of convective processes surface water becomes enriched i mineral nutrients due to the lower water layers.

1.6. Wind-induced waves in the Kara Sea.

The fetch value, one of the main factors, governing the development of wind-induced waves at different moments of the summer-fall period depends entirely on the ice cover extent. The fetch values in favourable years vary from 50-60 miles in early July to 400-450 miles and more in September.

In summer the occurrence frequency of the waves of 3 m and more is 8-10%, in the fall - 12-15%. And the strong waves are most often observed in the south-western and north-western parts of the Kara Sea.

In the south-western sea the ice rarely prevents the development of the maximum values of the wave heights, which can reach here 8 m (the length - 160 m, the period - 10 s). Strong waves of all directions are observed in this region;in summer the waves of north-eastern directions are most frequent. The central Kara Sea, where the depth and the fetches are rather limited

differs by an insignificant development of the wind-induced waves. With the storm waves penetrating this part of the sea from deep-water north-western and western regions the waves become more steep.

The data on the occurrence frequency of the wind-unduced waves are given in Table 1.5 [*The wind and waves in the oceans and the seas 1974*].

The wind-induced waves mix the upper water layer, contributing to the heat accumulation in summer and heat release in the fall. In shallow regions strong waves are able to destroy the pycnocline and mix the water practically to the bottom.

1.7. Water exchange

The water balance of the Kara Sea is composed of its water exchange through the straits and open sea boundaries with the adjacent oceanic and sea areas, river run-off, evaporation and precipitation.

The average annual volume of the river run-off into the Kara Sea is 1100 -1200 (taking into account small rivers) cu.km or about 0.03 Sv. And the share of Ob' is about 0.01 Sv and that of Yenisey - 0.02 Sv.

The amount of precipitation (20-30 cm a year) is approximately equal to the annual evaporation volume.

The inflow of the Barents Sea water through Kara Gate strait is estimated from 1240 cu.km/year (0.04 Sv) up to 20 000 cu.km/year (0.6 Sv), through the Yugorsky Shar - about 400 cu.km/year (0.01 Sv), through the strait between the islands of Novaya Zemlya and Franz-Josef Land - from 5 - 10 000 cu.km/year (0.15 - 0.3 Sv) up to 17 100 cu.km/year (0.54 Sv). The resulting water exchange between the Kara and Laptev Seas through Vil'kitsky strait is directed to the east and is estimated from 4 900 cu.km/year (0.16 Sv) up to 11 000 cu.km/year (0.3 Sv). The presented estimates were obtained both from field observations in different years and using computational methods [*Novicky 1961; Soviet Arctic 1970; Stepanov 1972; Timofeev 1961; Uralov 1961*].

Thus, an approximate estimate of the water exchange with the Arctic Basin through the boundary between Franz-Josef Land and

Table 1.5.

The occurrence frequency of the wind-induced waves in the Kara Sea.

Month	Prevailing wind direction	Frequency of the waves, % at a high, m				Elements of the waves		
		0-3	3-5	5-7	more 7	max high, m	length m	period, s
YII	from NW to NO	94	5	0.5	0.5			
YIII	from NW to NO, unstable	91	6	2.5	0.5			
IX	from SW in the southern part to SE and E in the nothern, unstable	86	10	3.5	0.5	8.4	160	10.1
X	in the western part unstable, in the eastern part from E and SE to SW	81	13	5.5	0.5			
	Mean over the summer-fall period	44	44	8	4	–	–	–

Severnaya Zemlya Archipelagos as follows from the zero water balance, shows the resulting northern direction of the flows from the Kara Sea with the volume of 19-22 000 cu. km /year (0.6 - 0.7 Sv).

One should note an approximate character of the estimates given in connection with a significant interannual, interseasonal and intraseasonal variability of the water flows through the straits.

The presented water exchange values allow us to estimate the values of the general ventilation period of the Kara Sea to be about 3.5 years.

1.8. Water circulation of the Kara Sea.

The characteristics of non-periodic currents of the Kara Sea is given to the currents only in the summertime of the year: August-first half of October, and only in the conditions of open water, i.e. in the absence of ice over the sea area considered.

The characteristics is mainly compiled from publications.

Non-periodic currents of the Kara Sea can be considered in the first approximation as a sum of two main components: permanent currents and wind-driven currents.

1.8.1. Permanent currents.

Permanent currents do not depend on the wind, acting at the present moment. They are formed under the effect of large-scale factors, which in principle act constantly, but are subjected to long-term fluctuations - of the order of season, year, etc. In the Kara Sea such factors are mainly the following ones: the location and intensity of the Icelandic Low and the Arctic High, water exchange with the Arctic Basin, the Barents and Laptev Seas, income of large volumes of freshwater, outflown by large rivers - Ob', Yenisey, Pyasina, etc. And the permanent currents of the Kara Sea change respectively.

Due to a relative stability in time and space, the permanent currents are considered to be the basis of sea water circulation, which governs the direction and intensity of all processes, related with a long-term advection of heat and salts, ice drift

and water exchange over large time intervals, etc.

That is why, the system of permanent currents and circulation of sea waters in this text are assumed to be of one and the same meaning.

The main flows, governing the circulation of surface water of the Kara Sea are considered to be the following permanent currents (Fig.1.20): Yamal'skoye (1), Ob'-Yeniseyskoye (2), East-Novozemel'skoye (3), "Sv. Anna"" (4), West-Taimyrskoye (5) currents [*Soviet Arctic 1970; Atlas of the Oceans, the Arctic Ocean 1980; Dobrovol'sky, Zalogin 1982*]. The Yamal'skoye current, a western periphery of the Ob'-Yeniseyskoye and East-Novozemel'skoye currents form a well-pronounced cyclonic circulation of surface water in the south-western sea, which produces a great influence on all hydrological processes, occurring here. The St. Anna current transports surface Kara water northward, outside the Kara Sea into the Arctic Basin, where it merges with the flow of the Transarctic current (6). The West-Taimyrskoye current, augmented by water of the Ob'-Yeniseyskoye current, governs water transport in the general direction to the north-east along the continental coast, to the eastern part of the sea, to the shores of Northern Land and the outflow of some portion through Vil'kitsky strait to the Laptev Sea. Part of the water, transported by the East-Novozemel'sky current, reaching the area of Kara Gate strait , flows with the Litke current to the Barents Sea.

The speeds of permanent currents over the largest sea area are not high. In coastal regions they exceed 10 cm/s only in some places, being less than 10 cm/s at a distance from the shores and less than 5 cm/s in the center of the cyclonic circulation in the south-western sea. Similar small speeds are typical also of the bays.

For example, in the Baidaratskaya Gulf, widely open toward the sea, the speeds are from 5 to 10 cm/s.

In the Ob' Gulf the speeds of permanent currents (outflow currents in the conditions of calm weather) at the surface, calculated from the hydrodynamic model [*Pavlov, Stanovoy 1983*] decrease from 7-12 cm/s in the southern part of the gulf to 4-6 cm/s in the middle part and 1-3 cm/s in the northern part of the

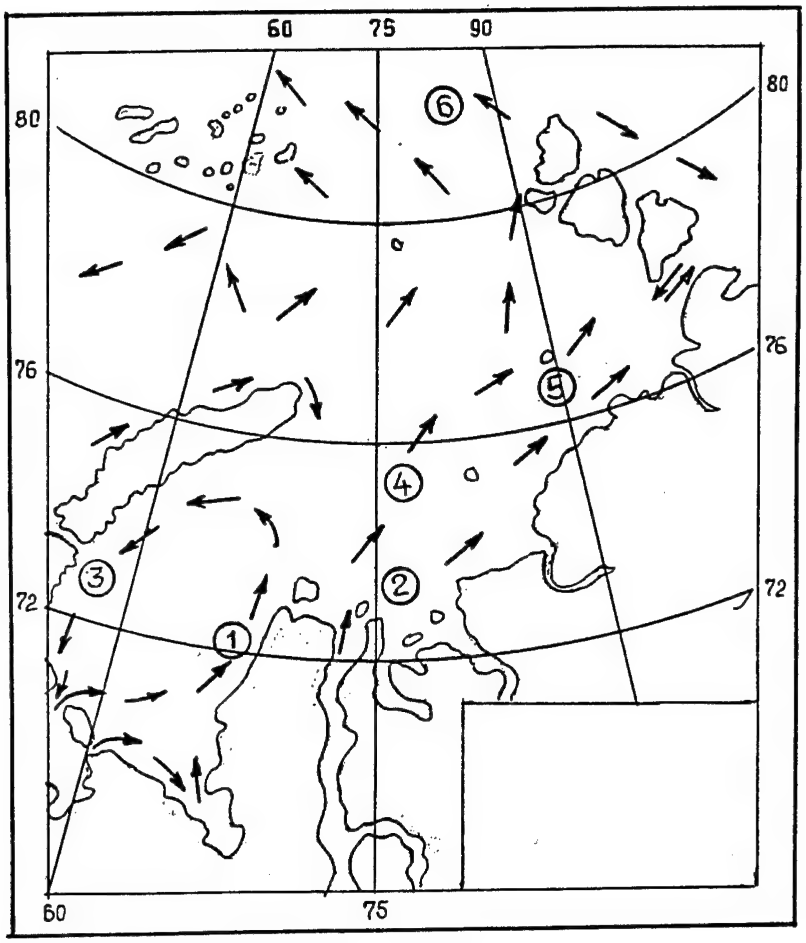


Fig. 1.20. Scheme of surface water circulation in the Kara Sea in summer.

Currents: 1 - Yamal'skoye, 2 - Ob'-Yeniseyskoye,
3 - East-Novozemel'skoye, 4. "St. Anna",
5 - West-Taimyrskoye, 6 - Transarctic.
[Dobrovol'skiy, Zalogin 1982]

gulf at the exit to the Kara Sea. In the Taz Gulf the speeds decrease from 3-5 cm/s in the southern part to 1-2 cm/s in the northern part at the exit to the Ob' Gulf. With depth the speeds decrease and near the bottom they are half as large as at the surface.

In the straits the currents are stronger, than in the open sea and in the bays. The permanent currents in the Southern Novozemelsky straits - the Kara Gate and Yugorsky Shar, calculated from field data [*Maksimov 1937; Maksimov 1938*] in the layer from 2 to 10 m, are shown in Fig. 1.21 and 1.22.

In a wide Kara Gate strait (mean strait width, equal to 61 km, is almost twice as large as the length equal to 33 km) the permanent currents (Fig.1.21) near the opposite shores have opposite directions. And the Litke current, carrying Kara water to the Barents Sea is much narrower and weaker (speed up to 25 m/s) than a strong Barents Sea current (the speed reaching in some places 65 m/s), directed to the Kara Sea.

In a narrow and long Yugorsky Shar strait (mean width is 8 km at a length of 40 km) the permanent current (Fig.1.22) over the entire strait area goes from the Barents Sea to the Kara Sea with a speed in some places up to 65-75 cm/s.

Barents water inflowing to the Kara Sea through the Kara Gate and Yugorsky Shar plays an important role in the formation of the Yamal'sky current.

As to the interannual changes of water circulation (the system of permanent currents) of the Kara Sea and other seas of the Siberian shelf, most well-pronounced and comparatively well studied appear to be those which are governed by the shifts of the Icelandic Low and the Arctic High of atmospheric pressure [*Gordiyenko, Karelin 1945; Soviet Arctic 1970; Shpaikher Fedorova, Yankina 1972; Nikiforov, Shpaikher 1980; Stepanov 1986, etc.*].

During the years of the predominant influence of the Icelandic Low on the Arctic on the whole (Fig.1.23.a) water transports from west to east develop in the seas of the Siberian shelf, in particular, the inflow of Barents water to the Kara Sea increases. Respectively, the Yamal'skoye, St.Anna and West-Taimyrskoye currents become stronger.

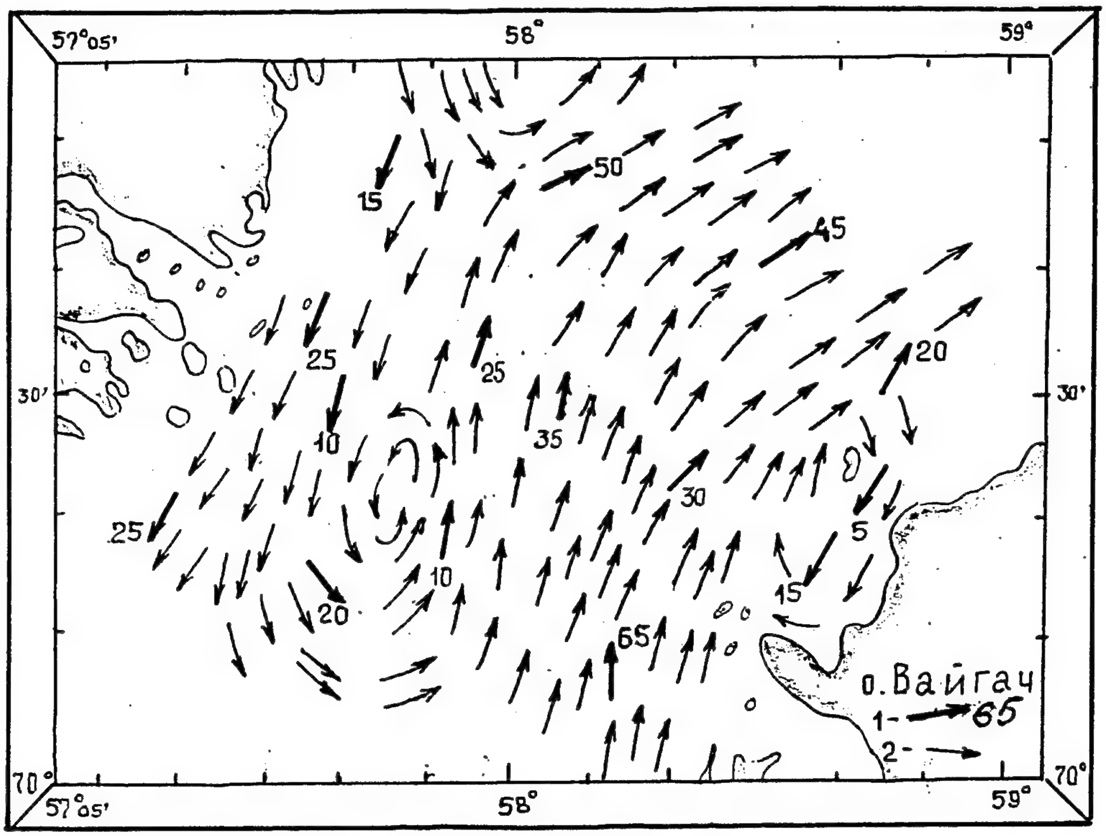


Fig. 1.21. Permanent currents in the layer from 2 to 10 m in Kara Gate strait in summer (in cm/s). 1 - from field data, 2 - suggested. [Maksimov 1937]

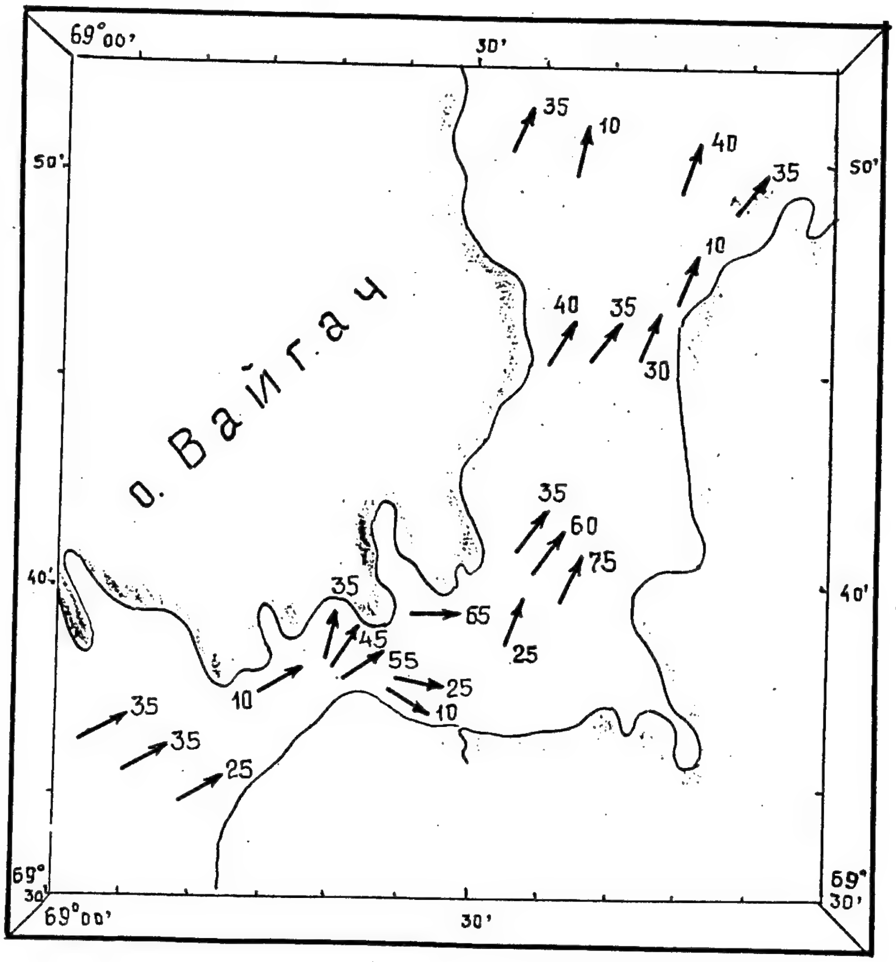


Fig. 1.22. Permanent currents in the layer from 2 to 10 m in Yugorsky Shar in summer (in cm/s). [Maksimov 1938]

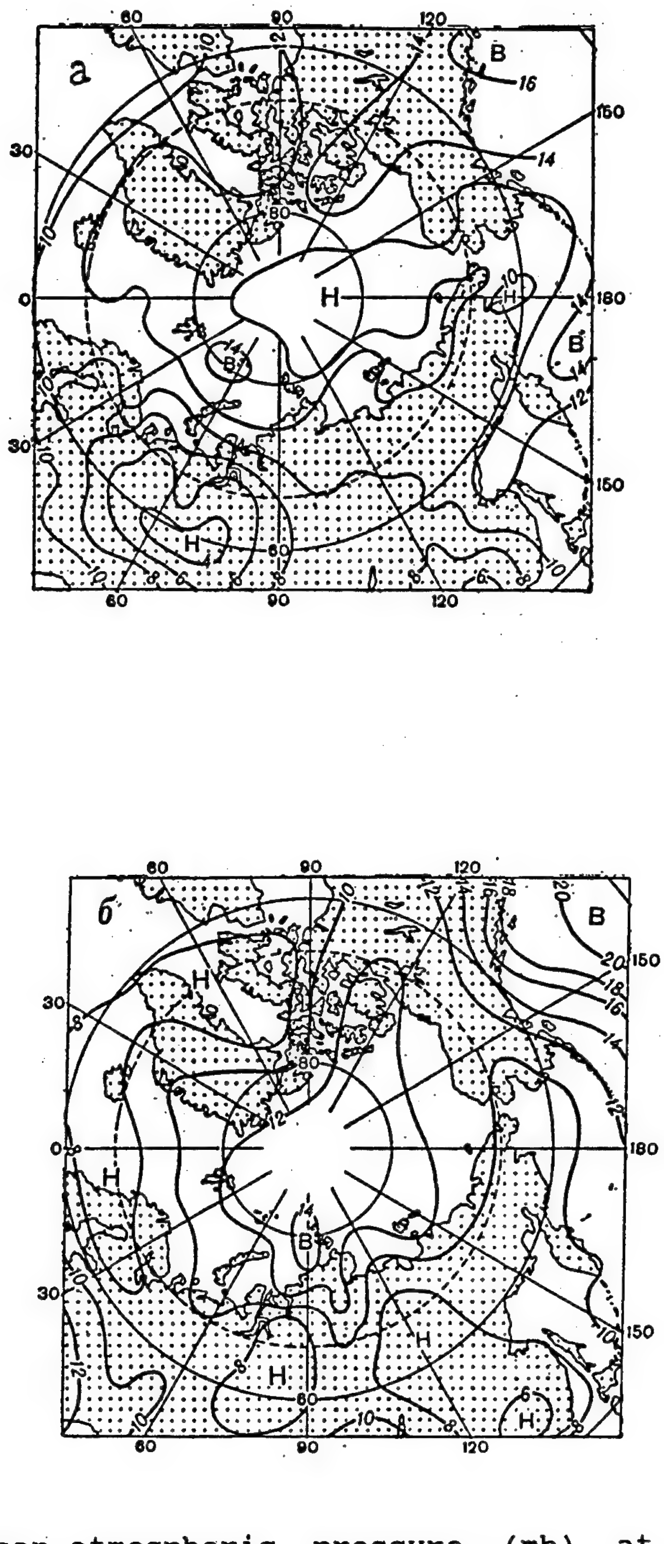


Fig. 1.23. Mean atmospheric pressure (mb) at a dominating influence of the Icelandic Low (a) and the Arctic High (b) in summer (from 1000 mb surface).
[Nikiforov, Shpaikher 1980]

The northward water outflow by the St.Anna current outside the sea limits is accelerated. The cyclonic water circulation covers the entire western sea region.

During the years, when the effect of the Arctic High prevails in the Arctic (Fig.1.23.b) the inflow of Barents water to the Kara Sea through Kara Gate and Yugorsky Shar straits is attenuated. The Yamal'skoye, St. Anna and West-Taimyrskoye currents are weaker. The cyclonic water gyre is restricted by the south-westernmost Kara Sea.

The interannual variations in the inflow of light fresh river water can also induce significant changes of the entire system of permanent currents, as shown by the results of calculating thermohaline water circulation from field data on temperature and salinity, made on the basis of hydrodynamic modeling [*Kulakov, Pavlov 1988; Doronin, Kuznetsov, Proshutinsky 1991, etc*]. Figure 1.24 shows results of the diagnostic modelling [*Kulakov, Pavlov 1988*]. This diagram reflect the main water circulation features of the Kara Sea.

1.8.2. Wind-driven currents

The wind-driven currents are induced by the wind acting at the present time and they change their characteristics, direction and speed in accordance with the changes of the wind field and the atmospheric pressure field. The "delay" of the current relative to the wind, which has caused it, depends on many conditions and is evaluated by different investigators differently, in most cases from 4 to 12 hours.

A combined analysis of field data on currents [*Baskakov 1986*] and the results of dividing pressure fields over the Kara Sea into types, developed by Seltser and Kuznetsov in 1988, has shown two types of the wind circulation of surface water to form in the Kara Sea in summer.

The first circulation type forms in those cases, when the center of a large cyclone, governing the wind field over the Kara Sea, is located northward or westward, and the anticyclone center, respectively, is southward or eastward of the middle sea part, for which the section of the Dikson island-Beliy island, approximately equidistant from the sea boundaries is assumed. In

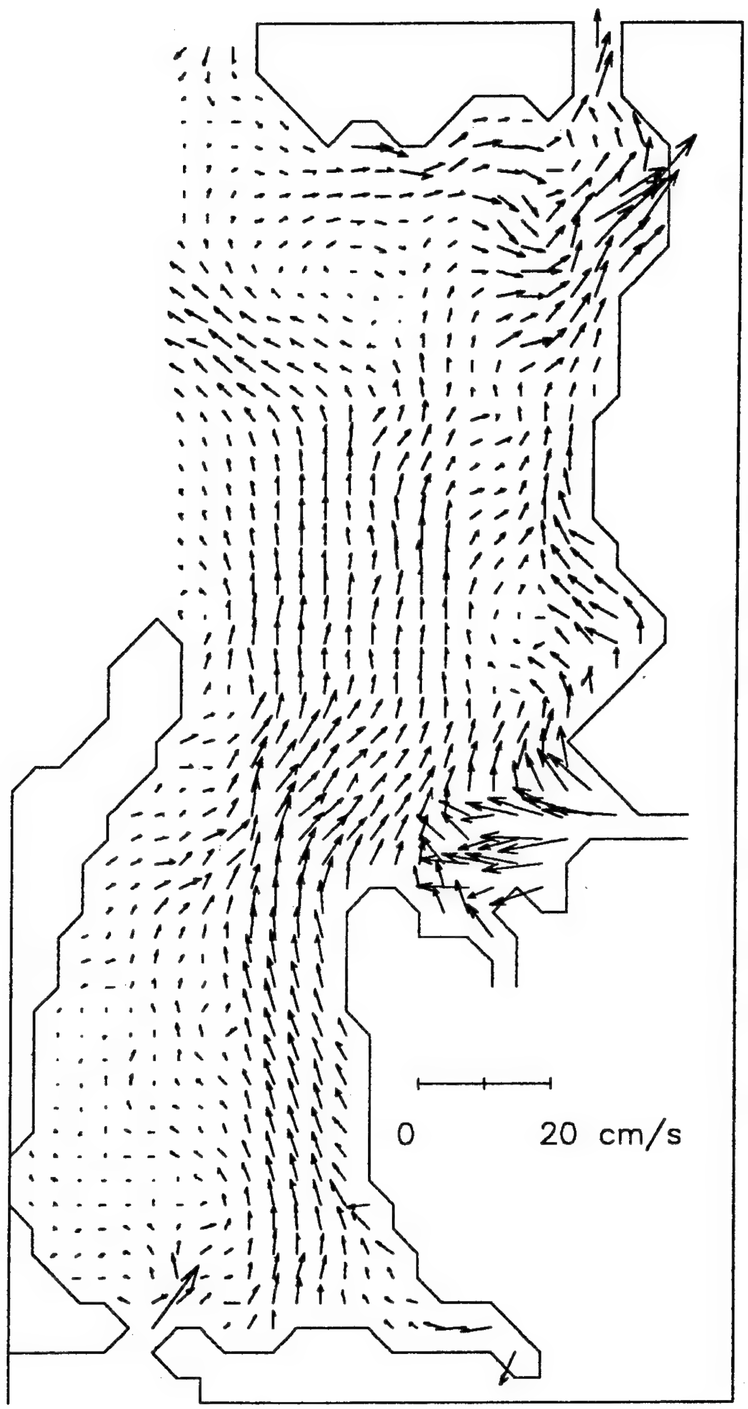


Fig. 1.24. Calculated scheme of the water circulation in the Kara Sea.
[Kulakov, Pavlov 1988]

such cases the winds of the southern half of the horizon prevail over the sea: south, south-west, south-east.

The second circulation type forms in those cases, when the cyclone center is located eastward or southward and the anticyclone center, respectively, is westward or northward of the middle sea part, and over which the north and north-east winds dominate.

Such winds cause over much of the sea area well-defined transports of surface water in the general direction from south-west to north-east at the first circulation type (Fig.1.25.a) and from north-east to south-west at the second circulation type (Fig.1.25.b). One can also suggest that off the eastern coast of Novaya Zemlya water goes southward at the first circulation type and northward at the second type. As a result, the cyclonic and anticyclonic wind water circulations are formed in the south-western sea region.

The current speeds, given in Fig.1.25.a and 1.25.b, correspond to the wind speeds from 5 to 10 m/s, prevailing here in summer. In the coastal regions the current speeds are usually slightly higher than 10 cm/s, being from 5 to 10 cm/s in the open sea and less than 5 cm/s in the center of the circulation.

According to multiyear data for 1956-1980 the occurrence frequency of winds, creating the circulation of water of the first type, is 36%, and of the second type - about 41% of the duration of the summertime (August-first half of October).

Non-periodic (outflow-wind-driven) currents of the Ob' Gulf at the surface, calculated on the basis of a hydrodynamic model [*Pavlov, Stanovoy 1983*] for the north, south, east and west winds of 5-10 m/s speed, prevailing here in summer, are shown in Fig.1.26.a and 1.26.b.

At the on-shore northerly wind (Fig.1.26.a) the current field presents a complex superposition of wind-driven currents, roughly equal by force, moving to the gulf and permanent currents (outflow currents during calm weather), moving from the gulf. Numerous wind formations are observed over the area of the Ob' and Taz gulfs. At the off-shore southerly wind, when the directions of the wind-driven and permanent currents in general

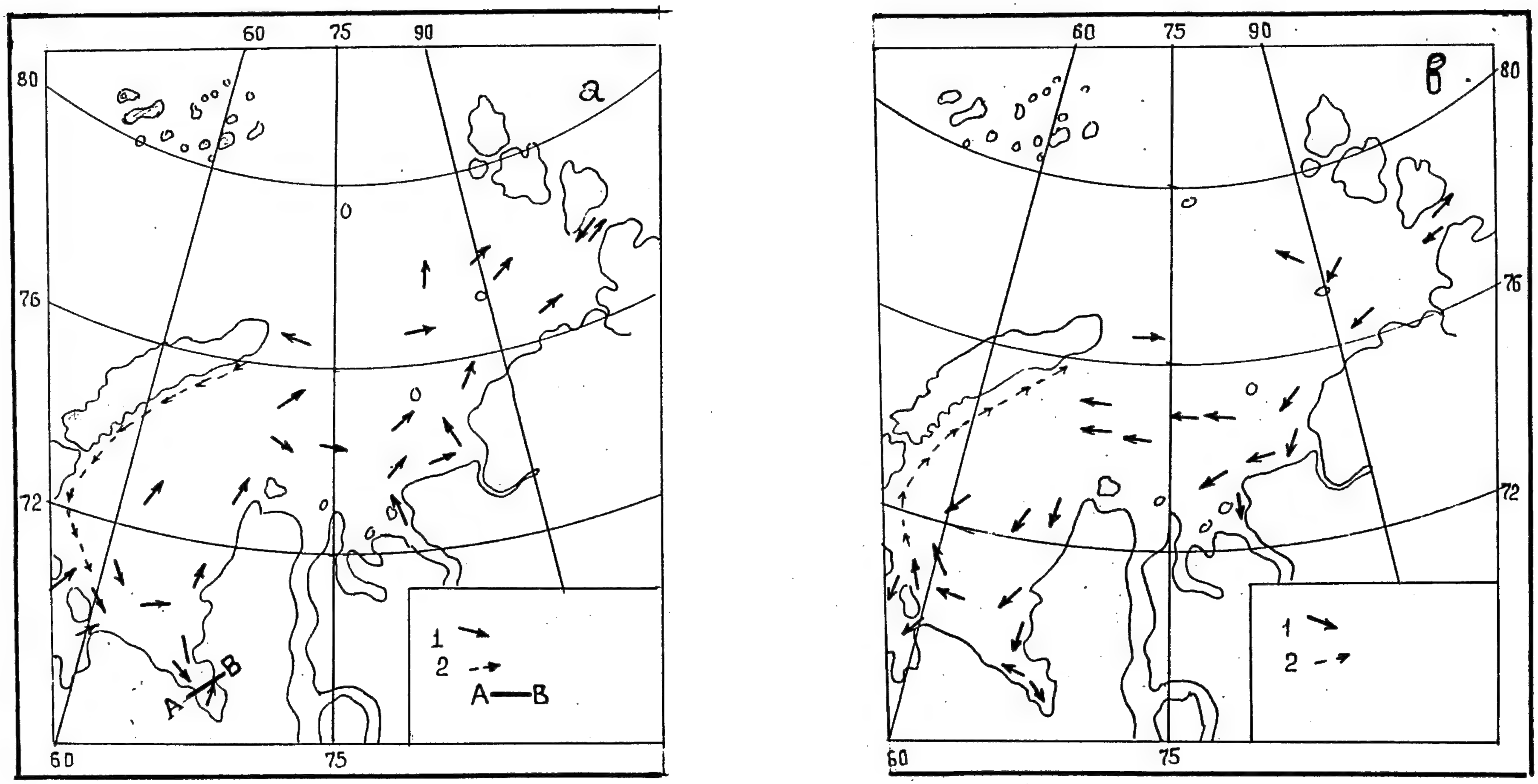


Fig.1.25. Wind-driven surface currents in the Kara Sea at the first (a) and second (b) types of pressure fields in summer. 1 - from field data, 2 - suggested.

[Baskakov 1986]

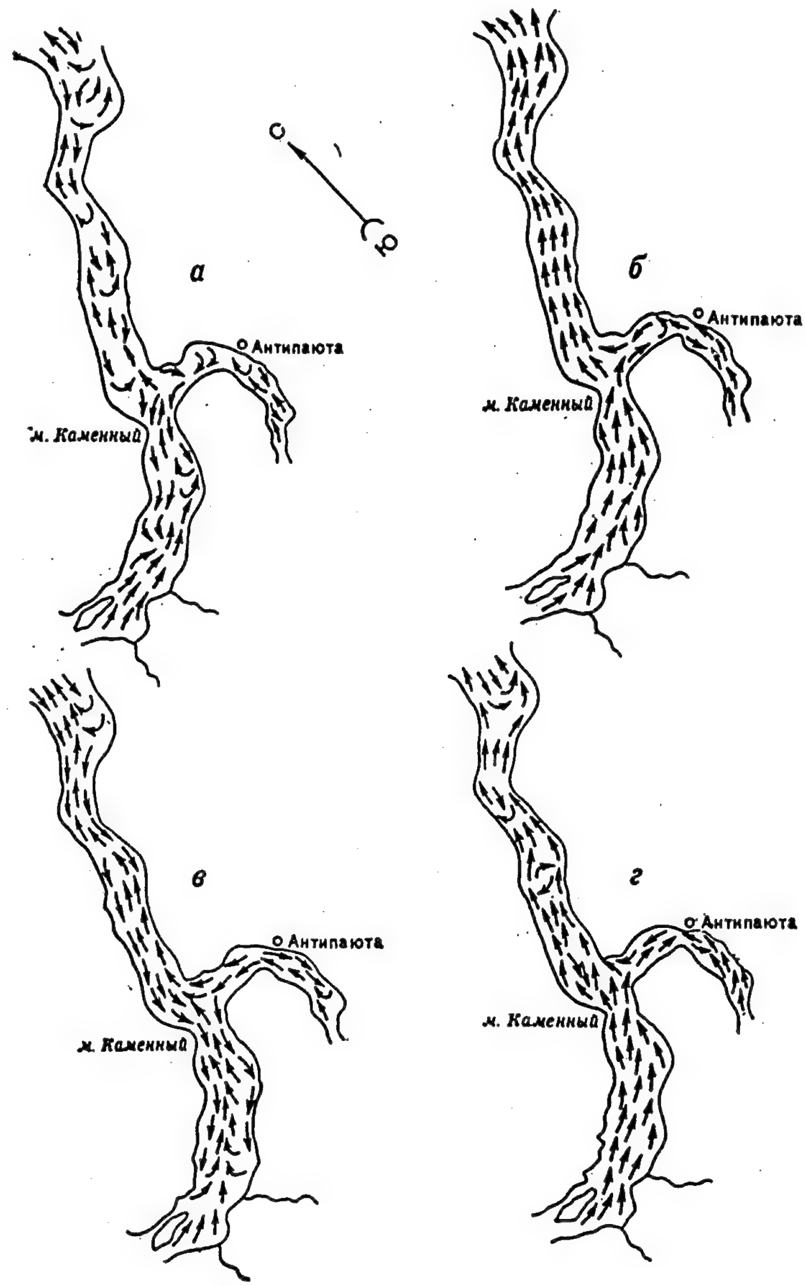


Fig. 1.26. Calculation schemes for non-periodic (outflow-wind-driven) currents at the surface of the Ob' Gulf at northerly (a), southerly (b), easterly (c), westerly (d) winds with a speed of 5-10 m/s in summer. [Pavlov, Stanovoy 1983]

coincide, the current field is sufficiently uniform (Fig.1.26.b).

The speeds of a non-periodic current at the surface change within a wide range, reaching 20 m/s in some places. With depth the speeds decrease, constituting in the near-bottom layer about half of the speed at the surface.

The maximum inflow of sea water to the gulf is observed in the surface layer at northerly and in the near-bottom layer - at southerly winds.

Wind-driven surface currents of the Kara Gate and Yugorsky Shar straits, calculated on the basis of the Ekman theory [*Maksimov 1937; Maksimov 1938*] for different wind directions and speeds are given in Table 1.6 and 1.7.

Table 1.6

Direction and speed (cm/s) of surface wind-driven currents in Kara Gate strait

Wind direction (from where)	Current direction	Wind speed (m/s)		
		6	10	14
N	218^0	27	45	58
E	274^0	14	23	32
S	38^0	27	45	58
W	94^0	14	23	32

As is seen from the data, given in these tables, at northerly winds the currents in both straits are directed from the Kara to the Barents Sea, and at southerly winds - from the Barents to the Kara Sea. The current speeds at such winds with a speed of 14-16 m/s can be 58 cm/s in the Kara Gate and 75 cm/s in the northern Yugorsky Shar. Easterlies and westerlies are favourable for the development of currents only in the southern Yugorsky Shar.

Table 1.7

Direction and speed (cm/s) of surface wind-driven currents in Yugorsky Shar strait

Wind direction (from where)	Northern strait				Southern strait			
	Current direction	Wind speed m/s			Current direction	Wind speed m/s		
		6	10	16		6	10	16
N	204^0	30	45	75	232^0	20	35	55
E	301^0	10	20	30	275^0	25	40	60
S	24^0	30	45	75	52^0	20	35	55
W	121^0	10	20	30	95^0	25	40	60

Note: meridian $60^0 30'$ is assumed to be the boundary between the northern and southern parts of the strait.

The wind-driven currents of the Baidaratskaya Gulf, calculated by means of a hydrodynamical model [*Polyakov, Dmitriyev 1993*] for the conditions of storm north-western winds with a speed of 22, 26 and 30 m/s over the south-western Kara Sea, are shown in Fig. 1.27. As is seen, with the wind increase the speed both of the surface drift current, directed to the Gulf and the gradient near-bottom counter-current from the gulf increases. And the thickness of the layer, occupied by the drift current decreases and that of the gradient current layer increases. There are no principal arguments against the obtained calculated maximum speeds of the drift current, exceeding 140 cm/s.

1.9. Tides

Two tidal waves come into the Kara Sea - from the Barents Sea and from the Arctic Basin, which merge to the north of the Ushakov island. The tides of the Kara Sea proper are small. The

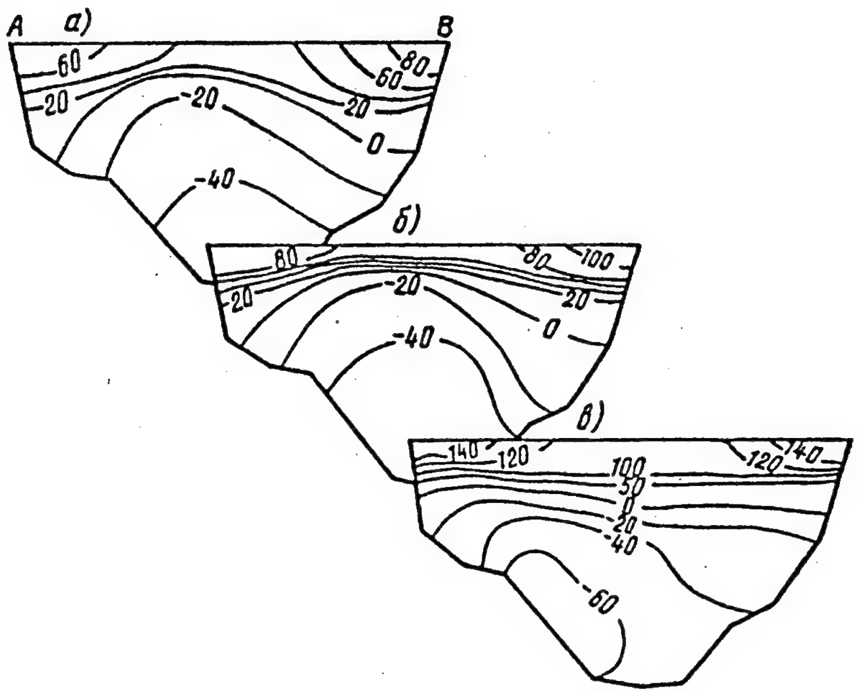


Fig. 1.27. Calculated speeds (cm/s) of wind-driven currents at the vertical AB section (see Fig.1.25.a) across the Baidaratsky Gulf at the north-west wind with a force of 22 (a), 26 (b), 30(c) m/s. The minus sign means that the current is from the gulf; no sign - the currents is to the gulf.

[Polyakov, Dmitriyev 1993]

waves, approaching the shores are returned and interferate. A characteristic feature appears to be the presence of the amphidromy of a semi-diurnal tide in the south-western part of the sea.

The values of the tide in the Kara Sea are on an average 0.5-0.8 m. (Fig. 1.28). The maximum tides are observed in the north of the Ob' Gulf, where on the western shore the tide values reach 1.8 m, and on the eastern shore (the Shokal'sky island) there is a weakly pronounced amphidromy with the tide value of 0.37 m. With the advance southward along the Gulf the tidal wave gradually dissipates up to 0.1 - 0.2 m in the south of the Gulf. In the northern part of the Yenisey Gulf the tide value is 0.3 - 0.5 m. Figure 1.29 show the diagrams of the propagation of the main components of the tidal waves [*Dmitriev, Proshutinskiy 1991; Soviet Arctic 1970; Tiron 1966*]. Along the shores of Novaya Zemlya the value of the tide reaches 0.5-0.9 m.

The tidal currents over the largest part of the sea have a semi-diurnal character, the zone with irregular semi-diurnal currents is situated in the coastal band near the Taimyr peninsula, in Kara Gate and Yugorsky Shar straits and near the Yamal peninsula.

One of the characteristic dynamic parameters of the tidal current appears to be its largest possible speed. The probability of reaching this speed is once in 18.6 years. The distribution of the largest possible speeds is governed by bottom topography, presence of islands and irregularity of the coastline. In open sea the maximum speed values are observed northward of the Ob' Gulf in the vicinity of the Beliy island, reaching 0.6 m/s and in the northern part of the Ob' Gulf near the western shore - up to 0.8 m/s. From this region to the other sea areas the speed values decrease and do not exceed 0.2 m /s in the deep water area as well as over the area, adjacent to the Taimyr peninsula. Near the islands, located in the deep-sea area, the speed increase up to 0.3-0.35 m/s is noted. The speed values also increase in the Baidaratsky Gulf and Yenisey Bay, reaching, respectively, 0.52 and 0.45 m/s. The most significant speeds of the largest possible tidal currents are observed in the straits Kara Gate (0.64 m/s), Yugorsky Shar (1.32 m/s) and Malygin (up to 0.82 m/s) straits

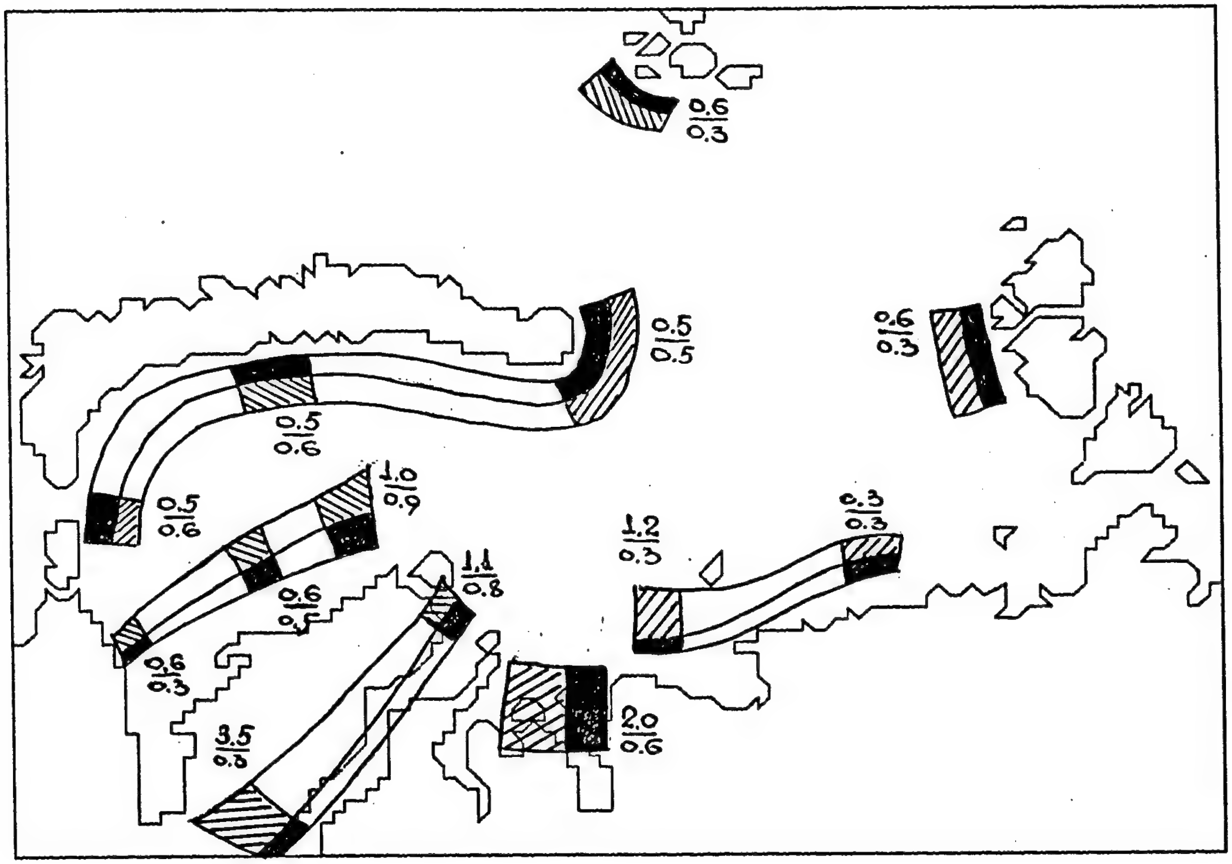
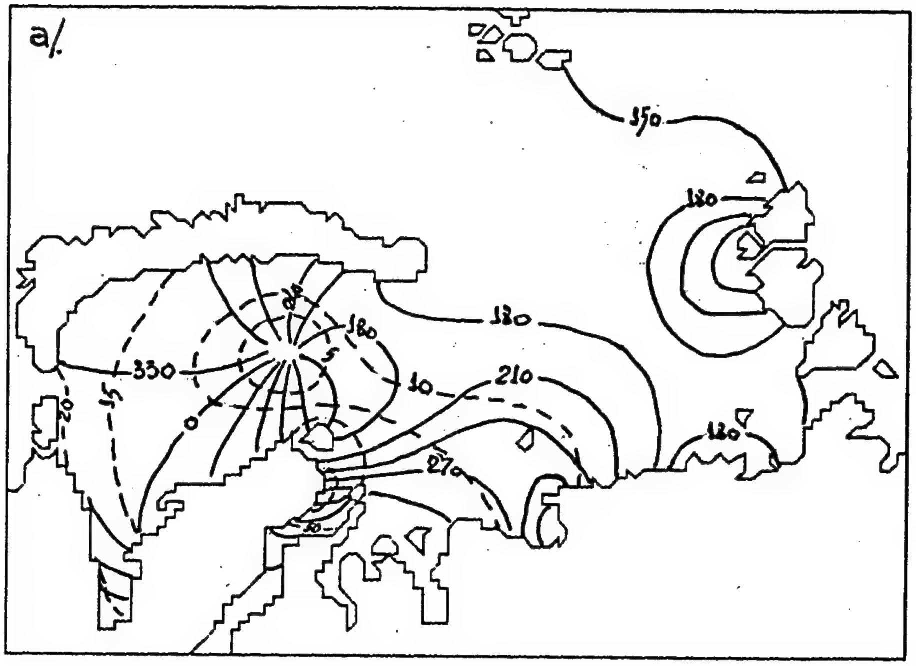


Fig. 1.28. Values of the storm surges (numerator) and tides (denominator).
[Soviet Arctic 1970]



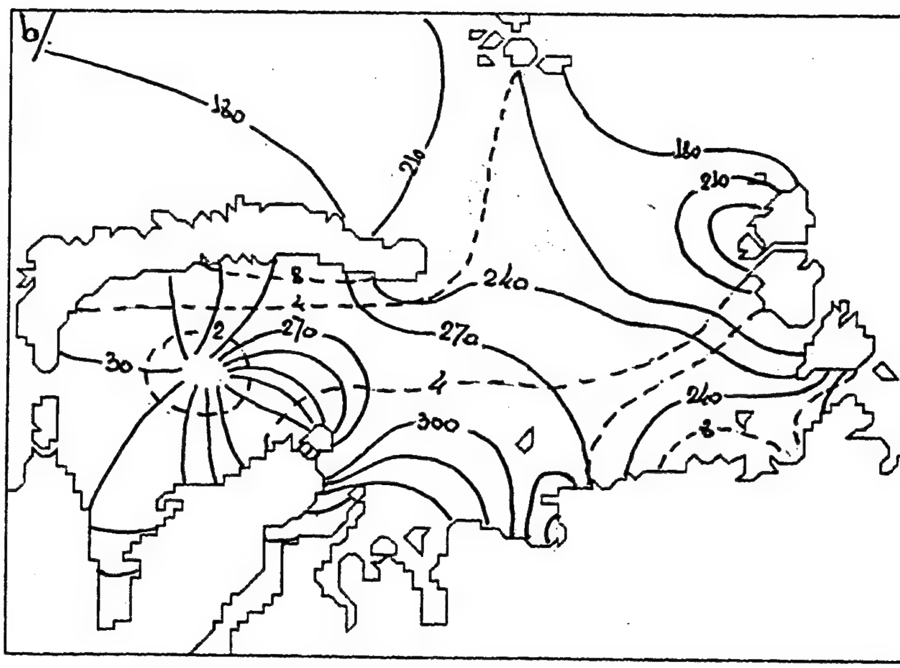


Fig.1.29. Scheme of the propagation of the main components of the tidal wave - M2 (a) and S2 (b)
[Dmitriev, Proshutinskiy 1991]

[*Voinov 1989*].

1.10. Level regime of the Kara Sea.

1.10.1. Annual and seasonal level fluctuations.

The multiyear level fluctuations of the Kara Sea are induced by large-scale changes of the hydrometeorological processes, covering the largest ocean portion. In addition to the atmospheric processes, causing the level increase or decrease, the interannual level changes can be induced by the interannual water density changes, which, in turn can result from the mean air temperature variations, intensity of the currents, changes in the river volume run-off. However, the most significant contribution is made by the atmospheric processes.

The mean rate of the multiyear change of the Kara Sea level is estimated to be 1.7 mm/year, that is, a tendency toward a level increase is observed [*Dvorkin, Mustafin 1977*].

The maximum interannual level changes vary from 10 to 18 cm and the contribution of the static effect of the atmospheric pressure depending on the region is 30-50%.

The deviations of the mean annual level from the mean multiyear one are 10-15 cm on an average over the sea, the changes having a periodic character. Along the coast of the mainland and in the central part of the sea the period of these changes is close to 20-22 years, and at the continental slope -10-12 years.

All sea regions are characterized by well-pronounced seasonal variations of sea level. From mean multiyear data the minimum level is observed in April, the maximum - in October and December. The value of seasonal level fluctuations in the western part of the sea is 18-20 cm, in the south-western - 27-31 cm, in the southern -20-24 cm and in the eastern - 13-16 cm [*Dvorkin, Zakharov, Mustafin 1979*].

The contribution of the wind component and the static effect of atmospheric pressure is 3-8 cm (in some years their contribution can reach 15-20 cm). The contribution of the density component reaches 4 cm. It reduces the level in March-June by 3-4

cm and raises in August-September by 3-4 cm [*Dvorkin, Zakharov, Mustafin 1979*].

1.10.2. Synoptic level fluctuations.

The level fluctuations of a synoptic scale have a mean duration of 4-6 days. In connection with the feature of the atmospheric processes over the Kara Sea (filled and slowly shifting cyclones) the main contribution to the synoptic level fluctuations is made by the wind stress, which induces water level to increase or drop near the shore. The surge phenomena can enhance due to the morphometry of the shores and the formation of local storm surges.

The maximum storm surges in the Kara Sea up to 3-3.5 m are observed in the inlets and bays of the southern coast (in the southern part of the Ob' Gulf and Yenisey Bay). Along the coast of Novaya Zemlya the surges have the values of 0.5-1.0 m, along the southern coast the surges are about 1 m and in the east of the sea - 0.5 - 0.6 m (Fig.1.28) [*Soviet Arctica 1970*].

1.11. Ice regime of the Kara Sea.

A severe climate of the highlatitudinal Kara Sea governs its complete freezing in the fall-winter time and a perennial ice existence.

The ice formation starts in September in the northern sea regions and in October in the south. From October to May almost the entire sea is covered with ice of different type and stage of development. On the average the area, occupied by ice is estimated to be 830 000 sq. km.

The coastal zone is occupied by fast ice (Fig.1.30.a). It is non-uniformly developed. In the south-eastern sea stranded ice forms a continuous band, extending from the Beliy island to the Nordenskjold archipelago and then to Northern Land. In the summertime this band of fast ice breaks up into ice floes. They are preserved for a long time in the form of the Severozemel'sky massif. Mean ice thickness in this sea part is 1.80 m. In the south-western sea fast ice occupies small areas. The ice

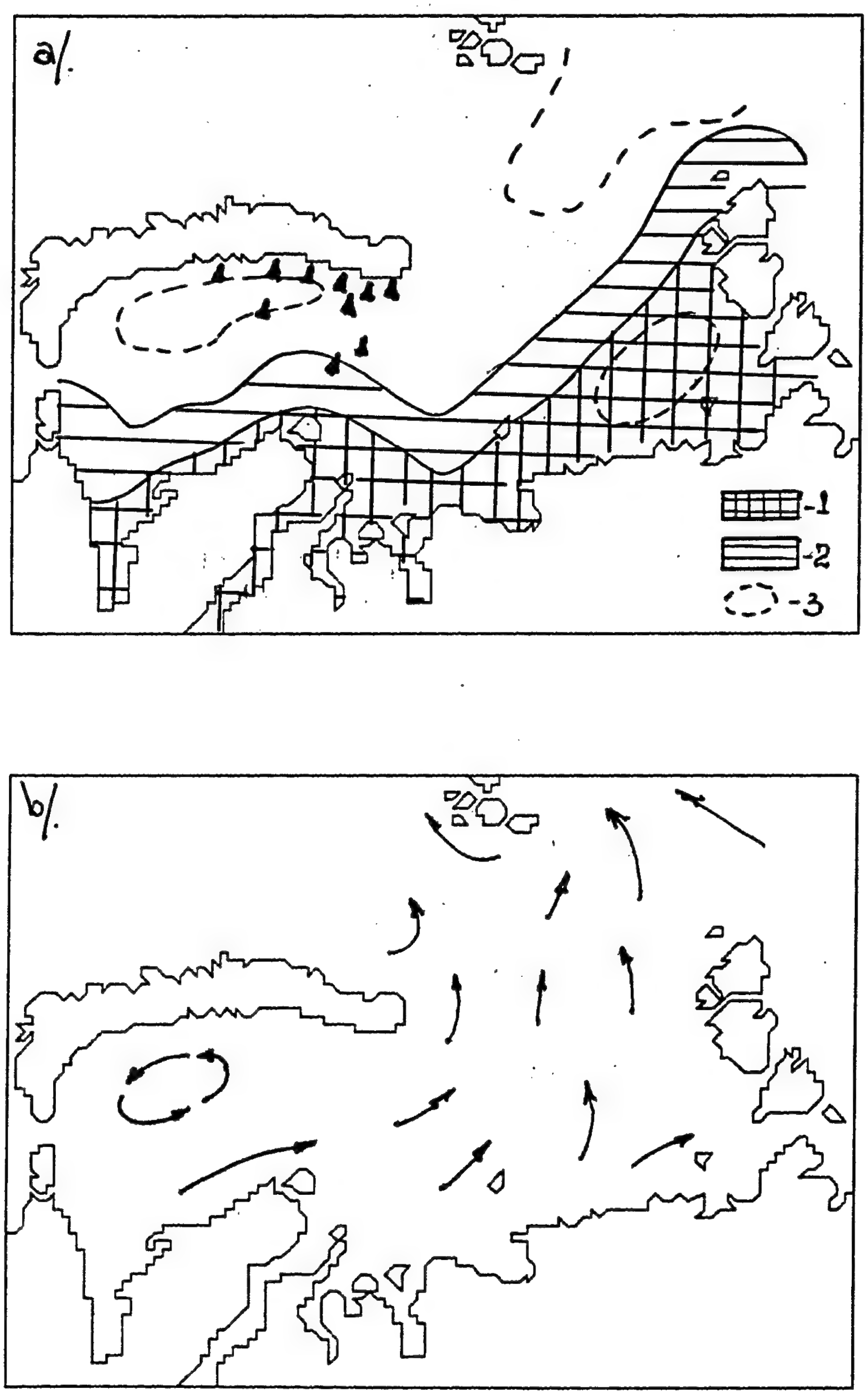


Fig.1.30. Ice cover of the Kara Sea (a) and scheme of the ice drift (b) [Romanov I.P.,1992].
1 - fast ice; 2 - zone of behind-fast polynyas;
3 - stable ice massivs; ▲ - positions of the observed icebergs.
[Soviet Arctic 1970; Romanov 1992]

thickness is about 1.20 m. One observes ice hummocking up to 20% of the area, the ratio of the ice thickness to the height of the hummocks is on an average about 0.91. Seeward of the stranded ice there is a zone of open water or young ice. This is the region of flaw polynyas. There are the Amderma and Yamal polynyas in the south-western sea part and the Ob'-Yenisey polynya - in the south of the sea [*Zakharov 1981; Soviet Arctica 1970*].

Off the shores of Novaya Zemlya there is the Novozemel'sky ice massif, which melts out in summer.

The drifting ice is wide spread in the central sea area, among which thick first-year ice of a local origin prevails. Its maximum thickness (in May) is 1.5-2 m. In the northern regions the ice persists all the time. Here the branches of oceanic ice massifs outflow. Ice concentration in the northern and north-eastern parts is up to 9-10/10, and in the south-western part - 5-8/10. The interannual amplitude of the concentration variations is 1 -3/10. The amount of hummocking is about 40% of the area with the ratio of the ice thickness to the height of the hummocks in this region - about 1.08 [*Romanov 1992*].

The outflow drift prevails in the sea, in the process of which the ice is exported northward (Fig.1.30.b). In the central sea the ice drift is quite intensive, but it slows in the northern sea (in some years no slowing occurs) and the ice joins the flow of the western ice transport in the Arctic Basin. From mean multiyear observation data the time of the ice export from the Kara Sea to Fram strait is 2 - 2.5 years [*Romanov 1992*].

In the spring period the drift in the Kara Sea has a prevailing westward and southward direction, in summer - to the south-west and south. Due to the south-western ice drift the ice in the northern sea regions at the southern approaches to Franz Josef Land is frequently preserved during the whole summer. In the south-western sea the ice moves by a cyclonic ring, often being preserved as a patch near the eastern shores of Novaya Zemlya during the whole summer. In the fall-winter period the prevailing ice drift is northward. In some years the outflow of river ice up to latitude 80^0 N was observed.

There is quite an intensive ice exchange of the Kara Sea with the Barents Sea through Kara Gate strait. From mean multiyear

data the ice import to the Kara Sea in the winter months (December-April) is about 98 000 sq. km and the export to the Barents Sea over the same period - about 21 000 sq.km . The volume of the drifting ice is on an average 4.6 cu.km a year [*Zubakin 1987; Kuznetsov 1983*]. The ice export through Vil'kitsky strait into the Laptev Sea is estimated to be 50 cu.km. The volume of the drifting ice between Novaya Zemlya and Franz-Josef Land is on an average 198 cu.km a year (maximum - in March-April - 44 cu.km). The total volume of the ice export from the Kara Sea to the Arctic Basin is estimated to be 170 cu.km.

The ice distribution in the spring-summer time depends on the prevailing wind and corresponding currents. The probability of open water in the south-western and central sea is 50-90%, in the northern and north-eastern - 10-30%.

2. THE LAPTEV SEA

2.1. Physical-geographical characteristics of the Laptev Sea.

The western boundary of the Laptev Sea passes along the eastern shores of Northern Land islands from the Arctic Cape (Komsomolets island) through Red Army strait along the eastern shore of the October Revolution island to the Anuchin cape, through Shokal'sky strait up to the Peschany cape to the Bol'shevik island and along its eastern coast to the Vaigach cape, then along the eastern boundary of Vil'kitsky strait and further along the continental shore up to the top of Khatanga Bay. The northern boundary of the sea passess from the Arktichesky cape up to the crossing point of the meridian of the northern tip of the Kotel'ny island (139^0E) with the edge of the continental shoal (79^0N, $139^0$00'E), the eastern boundary from the indicated point passes to the western coast of the Kotel'ny island, then along the western boundary of Sannikov strait, rounding the western shores of the Large and Small Lyakhovsky islands and then goes along the western boundary of Dmitry Laptev strait. The southern boundary of the sea goes by the continental shore from the Svyatoy Nos cape to the top of Khatanga Bay.

By its geograpghical location and hydrological conditions, differing from those of the ocean with which it is freely connected it is assigned to the type of the continental marginal seas.

The most significant islands of the Laptev Sea are located near its boundaries: near the western boundary - the Northern Land islands, near the eastern one - the New-Siberian islands. Off the south-western sea shore the islands of Komsomol'skaya Pravda, Peter and Large Begichev are considered to be the largest. The islands of the Laptev Sea are predominantly hillocky. The south-western shore is very irregular in some places.

The sea width along parallel 75^0 N between the Taimyr peninsula and Kotel'ny island is equal to 387 miles. The sea width from the Cheluskin cape to Dmitry Laptev strait is equal to

608 miles. The distance along the largest diagonal from the Manyko peninsula in Yana Bay to the Arctic cape of the Komsomolets island is equal to 999 miles.

The southern and south-eastern sea with depths from 10 to 50 m comprise around 45% of the entire sea area. The regions with depths less than 100 m constitute about 66% of the whole sea area [*Soviet Arctic 1979*].

Large depth differences are observed in the Laptev Sea. In its southern region the depths do not exceed 15-25 m, and the northern sea boundaries pass over the ocean bed with depths more than 2000 m. Mean depth of the Laptev Sea exceeds mean depths, characteristic of the shelf seas, due to the fact that its northern part includes a segment of the continental slope and the abysses of the Arctic Ocean. A dramatic depth drop, beginning with 100 m and ending at a 3000 m level, divides the sea by the isobath into the northern and southern parts almost along the parallel of the B.Vil'kitsky strait [*World ocean Altas, volume 3, Arctic Ocean 1980; Dobrovolskiy, Zalogin 1982*].

2.2. Meteorological regime and climate

The climate severity of the Laptev Sea is mainly governed by its high-latitudinal position. Due to the location of the sea north of the Polar Circle, polar night is observed here, its duration increasing from 70-80 days in the southern sea to 100-120 days in the northern part. Polar day due to refraction is by about 16 days longer than polar night. During polar day the largest height of the Sun does not exceed 40-42 degrees in the south of the sea and 32 degrees at the latitude of the northern tip of Northern Land.

2.2.1. Radiation

The annual influx of total solar radiation to the sea surface constitutes 2700-2900 Mj/sq.m. About 70% of total solar radiation is contributed by scatterred radiation. The maximum input of solar radiation is observed in May-June (45-50% of the annual sum). However, due to a large reflectivity of snow and ice about half of the solar radiation, incoming to the underlying

surface, is reflected back to the atmosphere and only 1000-1400 Mj/sq.m a year is absorbed by it. And while the largest radiation input is noted in May-June, the maximum radiation absorption is typical of July, when snow cover melts out completely [*Chernigovsky, Marshunova 1965*].

The radiation balance of the underlying surface is an indicative characteristics of the radiation regime.

Fig. 2.1 presents distribution of the annual radiation balance. Lines on the map denote equal radiation balance values in kcal per cm a year. As is evident from Fig. 2.1, the radiation balance of the underlying surface in the Laptev Sea is positive over the year. However, during much of the year (September-April) the radiation balance of the sea is negative. During the summer months (May, June, July, August) the radiation balance, particularly during the central summer months, reaches large values, which form positive values over the year.

Fig. 2.2 shows maps of the radiation balance distribution in January and July. In the wintertime the negative radiation balance over the sea is uniform. In the summertime the radiation balance values increase from north to south. In the southern sea in summer its values are comparable with those in midlle latitudes.

2.2.2. Underlying surface

The climate of the Laptev Sea is, to a great extent, governed by the state of the underlying surface. The main effects on the climate are produced by the current, ice cover extent, orography of the coastal continental zone.

During the summer months the climate is strongly affected by sea currents: the cold East-Taimyrskoye and warm Lena Currents. As a result, in the western part the sea is cold with frequent fogs and a considerable cloud cover. Most favourable climatic conditions are observed in the southern sea zone under the influence of the warmed Siberian mainland and a warm Lena Current.

Much of the year the sea is covered by solid ice and snow cover. By early September all coast and most of the sea become free of ice and snow, but in October all sea becomes again

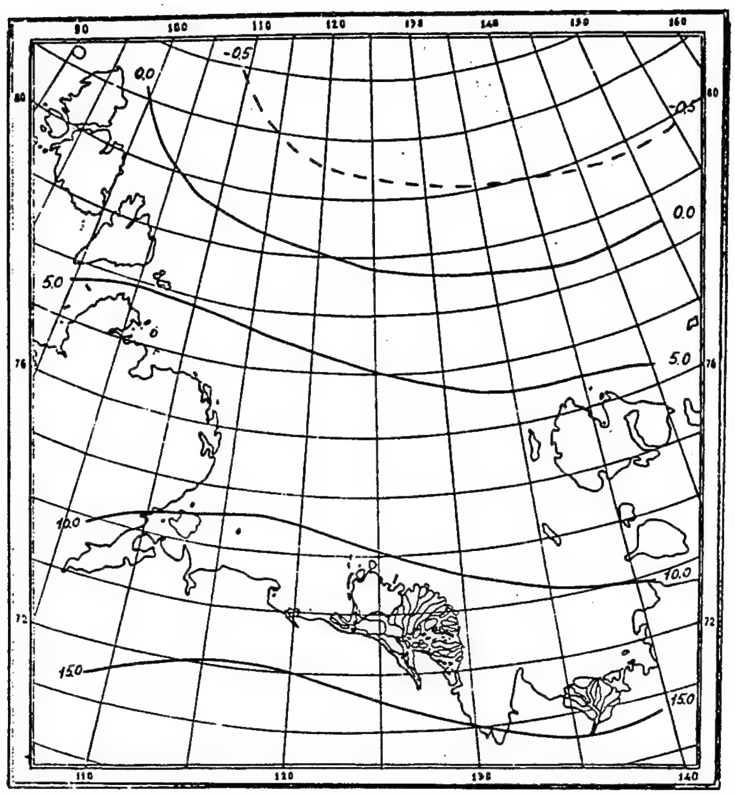


Fig 2.1. Distribution of the annual radiation balance (Kkal/year$\cdot$cm^2) of the underlying surface in the Laptev Sea [Chernigovsky, Marshunova 1965].

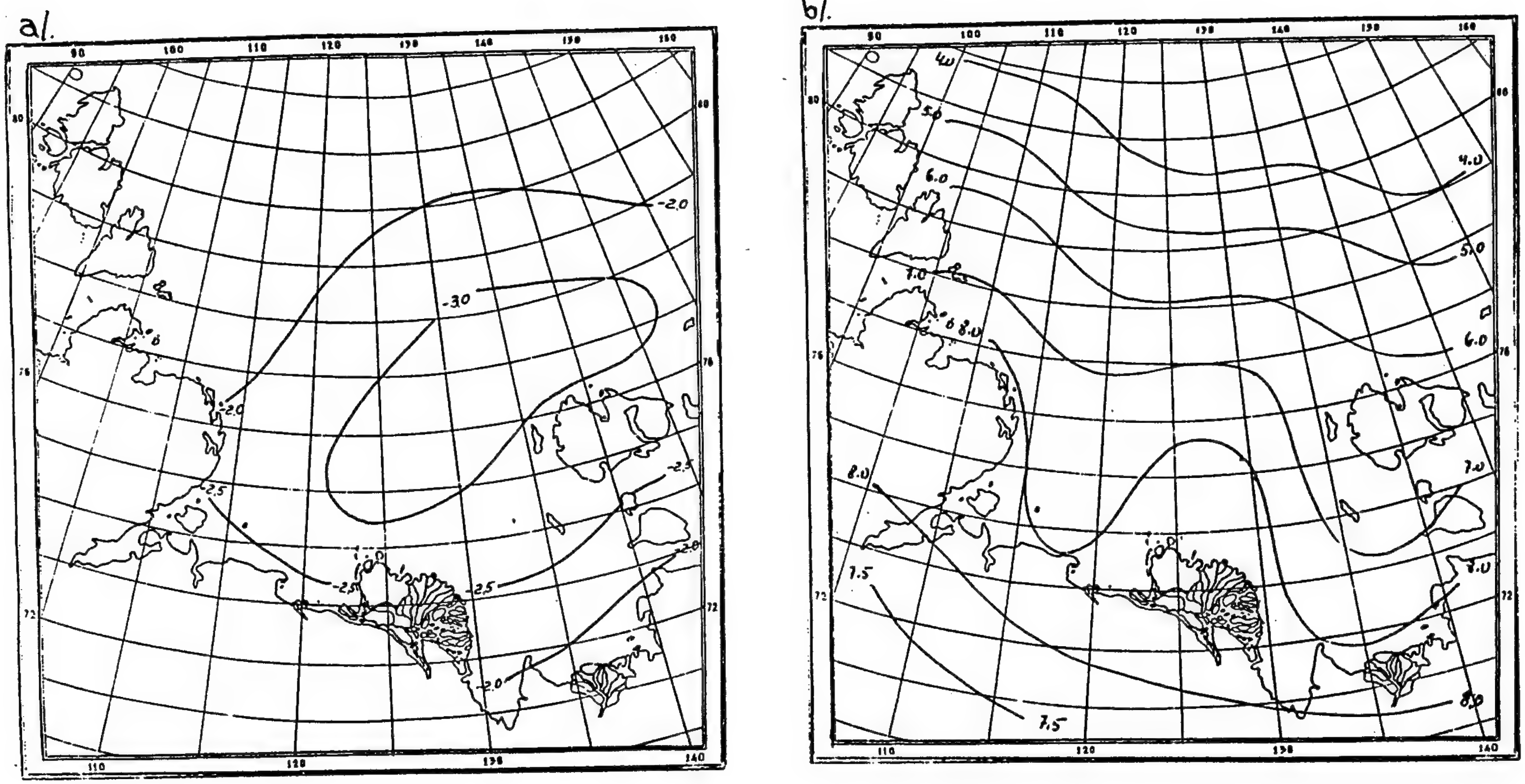


Fig 2.2. Distribution of the radiation balance (Kkal/month·cm^2) of the underlying surface in the Laptev Sea (a) - for January and (b) - for July. [Chernigovsky, Marshunova 1965].

ice covered. The position of the ice edge influences considerably weather conditions of the summer months. Sharp contrasts of absorbed radiation and air temperature are related with the ice edge. In winter ice serves as a regulator of heat exchange between the sea and the atmosphere. The coastal zone orography affects the wind and thermal regimes [*Climate features 1985*].

2.2.3. Atmospheric circulation

Atmospheric circulation in this region has a well-pronounced seasonal character. In the wintertime (Fig.2.3.a) it is governed by the effect of two centers of the atmosphere - the Icelandic Low and the Asian High. From November to March much of the sea area is under the effect of the Icelandic Low trough. Only the south-eastern part is influenced by the protrusion of the Siberian High. Such distribution of atmospheric pressure contributes to the development of a winter monsoon, which is expressed in the prevailing air flows from the continent to the sea. Along the trough, on an average 2-3 times a month, the cyclones of the Atlantic origin exit at a well-pronounced west-eastern transport of air masses in the Arctic. These cyclones make the sea climate appreciably more mild in the wintertime [*Soviet Arctic 1970; Prik 1959*].

The change in the pattern of atmospheric processes from the winter circulation to a spring one is observed in April-May. It is characterized by the fact that over the region of West Siberia (regions of Yakutiya) a seasonal cyclonic depression is formed, which represents a set of the cyclones of mainly thermal origin, governed by an active spring warming of the underlying continental surface. The elevated pressure ridge from the Arctic anticyclone forms over the cold sea (Fig.2.3.b).

This ridge is occasionally destroyed by rare exits of cyclones from the Kara Sea and small gradient cyclones from the south.

During the summer months (Fig.2.3.c) the northern Laptev Sea is predominantly under the effect of the southern periphery of the Arctic anticyclone. The southern sea periphery is affected by the Siberian depression of decreased pressure. A small gradient anticyclonic field is occasionally destroyed by deep cyclones,

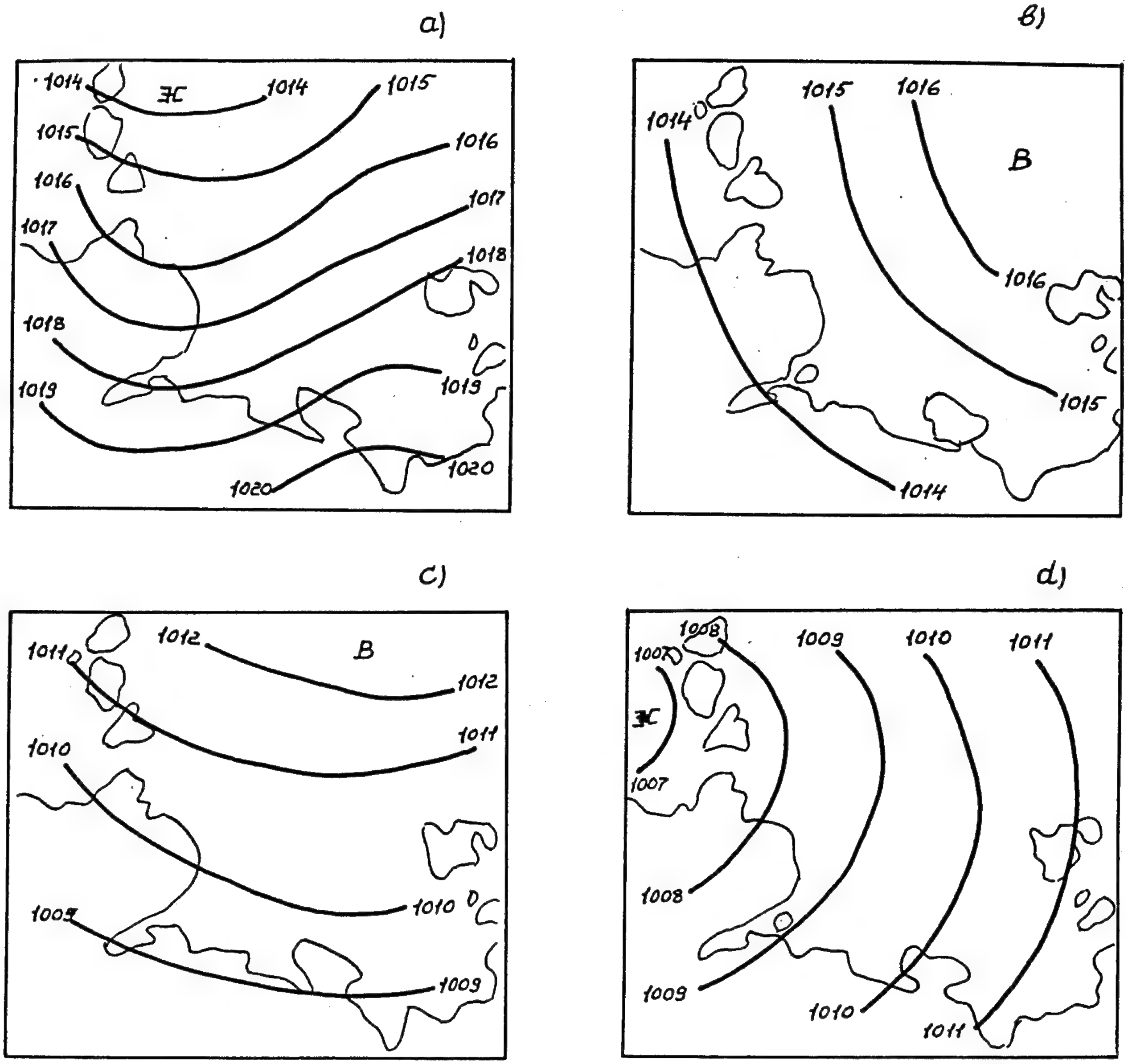


Fig. 2.3. The seasonal distribution of pressure fields over the Laptev Sea
a) in winter, b) in spring,
c) in summer, d) in autumn.
[Soviet Arctic 1970]

moving from west to east from the Kara Sea at the west-eastern transport of air masses in the Arctic. The cyclone exits from the west to the Laptev Sea are observed not more than 2-3 times a month. More often there are observed over the sea the cyclone exits from the south and south-west. The southern cyclones bring warm air masses to the sea from tundra.

The change of the pressure field pattern from summer to the fall in the Laptev Sea occurs by means of the increase of the number of cyclones, shifting from the Kara Sea toward the Laptev Sea. As a result of increased frequency of western cyclones, mean pressure field forms over the sea (Fig.2.3.d). The isobars are located in the mean pressure field in such a way that the area of decreased pressure area is observed over the western sea region. The eastern region is under the effect of high pressure field.

2.2.4. Wind regime

Multiyear occurrence frequency of the directions of air flows over the Laptev Sea is governed by mean pressure fields, presented in Fig. 2.4.

In winter (Fig.2.4.a) the prevailing directions of the wind transfer appear to be south-western, western and north-western ones. The winds of other directions are equally probable and do not exceed 10% of the occurrence frequency level.

In spring (Fig.2.4.b), in connection with the change of the pattern to the anticyclonic field, the prevailing transports of air masses are in the eastern and south-eastern directions. Air transports of south-western and western directions are more seldom.

In summer as in spring, the prevailing air transports are in the eastern directions (Fig.2.4.c). Along with the eastern directions the enhanced frequency of the south-western directions is observed as well. The latter are related with the cyclone exits to the sea.

The fall period is characterized (Fig.2.4.d) by south-western and southern transports of air masses. In the fall in the Laptev Sea one observes most often the exits of cyclones from the side of the Icelandic depression. And the frontal parts of these cyclones create stable western and south-western

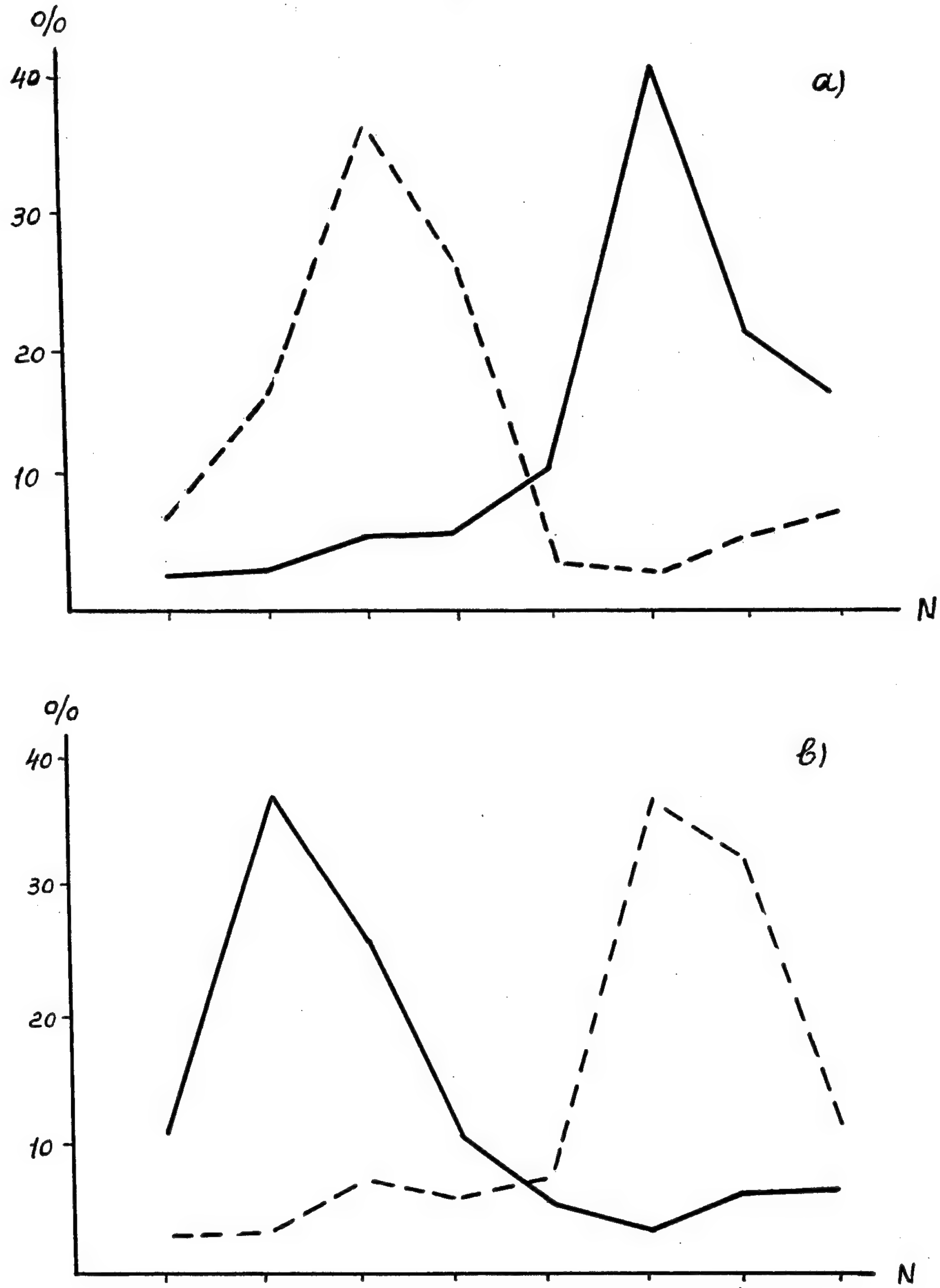


Fig. 2.4. Multiyear occurrence frequency of the directions of air flows over the Laptev Sea

a) ——— winter, ----- spring,

b) ——— summer, ----- autumn.

[Atlas of the oceans. The Arctic Ocean. 1980]

transports of air masses over the sea.

Mean wind speeds over the Laptev Sea area change insignificantly from season to season [*Soviet Arctic 1970; Climate features 1985*], their annual amplitude usually not exceeding 2-3 m/s.

Over the eastern sea the largest wind speeds are observed in summer. Over the other sea regions the wind maxima are noted in winter and in transient seasons (spring, fall).

The speeds depend, to a great extent, on the wind direction. Mean speeds of the winds of different directions can differ by 2-3 times, especially in winter. In the western sea the most strong winds appear to be the winds of western directions. Their speeds exceed mean wind speeds by 1.5 times. In the vicinity of the New-Siberian islands large speeds are observed at winds of eastern and north-eastern directions.

Most interesting appear to be the data on the occurrence frequency of storm winds (>15m/s). The number of days with storm winds at the sea coast is 40-50 times a year. In open sea the storms are observed during a colder half of the year (3-4 times a month). In summer the number of the days with storms decreases to 1-2. But due to a comparatively short duration of the storms, their total occurrence throughout the year in the open part constitutes 2% of the total number of observations of the wind speed. During the fall-winter period storm winds in the western and eastern sea near Vil'kitsky and Laptev straits constitute 5%. By duration the storm winds in the Laptev Sea do not exceed 6 h and only in single cases persist during 3 days.

The Laptev Sea is characterized by the occurrence of weak winds (< 5 m/s) during the whole year. The largest occurrence frequency is typical of winter and spring, being 50% of all cases.

Table.2.1 shows mean and maximum number of days with strong winds for each month and on the whole for the year.

2.2.5. Temperature

A peculiar temperature regime of the Laptev Sea is governed by the continental character of this region, related with its being remote from the Icelandic and Aleutian Lows and the

Table 2.1

Mean and maximum number of days with strong wind
(more than 15 m/s)

Regions	Months											
	1	2	3	4	5	6	7	8	9	10	11	12	Year
Western	3	5	5	4	4	4	3	6	3	6	6	7	56
Laptev Sea	6	10	8	10	6	10	7	7	7	10	8	10	99
Eastern	8	7	6	4	2	2	2	2	3	6	6	7	55
Laptev Sea	19	19	14	14	8	6	5	6	7	15	14	15	142
Novosibirskiye	4	3	3	5	2	2	3	4	2	4	2	3	37
islands	9	9	6	8	8	4	7	5	10	5	7	5	83

Note: mean - in the numerator, maximum days with strong wind - in the denominator.

dominating effect of the Siberian High in the wintertime. As a result, record values of annual fluctuations of mean monthly air temperatures, reaching 52^0-54^0 in the southern sea and 30^0 - in the northern part, are observed.

Most homogenous temperature conditions at sea are recorded in winter.

During the winter months along the coast the air temperature is -30^0 - -32^0 C, being -29^0 C over the sea area. Since April the radiation factor of the temperature regime formation is the governing one and the temperature increases from north to south from -21^0 - - 22^0 C to -19^0 - 20^0 C.

During the summer months the mainland is strongly heated and the coastal zone is characterized by significant temperature

gradients. In July and August the temperature off the coasts decreases from 8^0 to 2^0 C. The summer temperature over the sea area is, on an average, close to zero. In September positive temperatures are preserved only south of 75^0 N. Northward the temperature rapidly decreases up to -6^0 C. In October over the southern sea there is a source of elevated temperatures (-10^0 C), to the north and south of it the temperature sharply decreases. In November the winter type of temperature distribution is established, which is characterized by its increase northward [*Prik 1959; Climate features 1985*].

Table 2.2 presents mean monthly temperatures and their absolute maxima and minima by months and on the whole for the year.

In some years mean monthly temperatures can significantly deviate from mean multiyear ones. In winter the amplitude of their variations is $10\text{-}11^0$, in the eastern sea and along the Taimyr coast it reaches $15\text{-}17^0$ C. In summer the amplitude of variations is 2.5^0 C.

Frosty weather persists much of the year in the Laptev Sea. The duration of the period with positive mean daily temperatures is about 2 months in the northern sea and 3-3.5 months in the southern sea region. A stable temperature transition across 0^0 in the southern sea in observed on July 10, and in the northern part in early August. Early and late dates of a stable temperature transition across 0^0 can differ from each other by a month and more than a month.

In the fall a stable temperature transition across 0^0 in the south is observed in late September and in the middle of August - in the central sea.

The range of possible temperature variations, characterized by absolute extreme values over the Laptev Sea, is large. In the winter months a possible amplitude of variations is $50\text{-}60^0$ C, in summer - $25\text{-}35^0$ C.

The air temperature over the Laptev Sea is closely connected with the wind regime and clouds.

2.2.6. Cloud, precipitation

The main characteristics of the moistening regime are

Table 2.2

Mean monthly (1), absolute minimum (2), absolute maximum (3) of air temperature (°C)

Regions	N	Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Western Laptev Sea	1	-30.8	-28.7	-27.5	-19.7	-8.7	0.4	3.7	3.5	-0.4	-9.7	-21.7	-26.4	-13.8
	2	-49	-50	-47	-41	-32	-18	-5	-6	-19	-31	-43	-46	-50
	3	-1	-2	-4	4	12	20	25	22	15	7	0	-1	25
Eastern Laptev Sea	1	-33.3	-31.3	-26.3	-18.1	-6.9	2.5	7.0	7.5	1.7	-10.3	-23.9	-24.8	-13.4
	2	-52	-54	-49	-47	-33	-14	-3	-4	-20	-37	-45	-50	-54
	3	-4	-5	-1	6	24	33	33	29	20	7	-4	-3	33
New-Siberian islands	1	-29.5	-29.9	-28.1	-20.8	-9.3	0.2	2.5	2.0	-1.6	-10.5	-21.7	-26.7	-14.5
	2	-48	-49	-48	-46	-30	-12	-4	-6	-20	-37	-40	-43	-49
	3	-5	-3	-9	0	9	21	22	22	11	5	-3	-3	22

considered to be clouds, humidity and precipitation. In accordance with the atmospheric circulation conditions the cloud cover of the Laptev Sea is characterized by very distinct annual variations with the maximum in summer and minimum in winter. Mean cloud cover in winter is equal to 40-50%, from July to September it is 80-90%.

The air humidity over the sea depends on moisture content of air masses and temperature. A relative air humidity over the sea is large throughout the year. The largest values of relative humidity in the region are observed in summer, being 85-90%.

Frequent occurrence of precipitation is related to a great extent with high relative humidity. Over the Laptev Sea, on an average, for a year there are observed 140-180 days with precipitation. During the summer-fall period the number of days with precipitation is by 1.5 times larger than in winter. On an average during the year 200-250 mm falls out over the Laptev Sea. Precipitation is more frequent in October, constituting 45% of the annual norm. The least precipitation amount (in the form of snow) is observed in February-April.

2.2.7. Dangerous phenomena

Dangerous weather phenomena include fog and drifting snow. Fogs are considered to be a typical feature of the climate of the Laptev Sea in summer. In the coastal regions 40-60 days with fogs are recorded on an average over the year. In the northern sea the fogs are observed up to 100-120 days. The largest number of days with fogs are in July-August.

Table 2.3 presents mean and maximum number of days with fogs by months and on the whole over the year.

The fogs of the Laptev Sea in summer are connected with the advection of warm and moist air to the cold underlying surface. They cover considerable areas, differ by a large vertical thickness, duration and sudden appearance.

While for the short Arctic summer the fog is considered to be a dangerous phenomenon, for the colder time of the year (October-May) it is drifting snow. From 60 to 100 days with drifting snow are observed throughout the year.

Table 2.3

Mean and maximum number of days with fogs

Regions	1	2	3	4	5	6	7	8	9	10	11	12	Year
Western Laptev Sea	1/5	2/5	1/4	2/7	4/10	10/16	12/21	13/22	7/20	2/5	1/5	1/4	56/124
Eastern Laptev Sea	2/7	1/2	2/4	3/7	6/14	12/20	11/23	6/13	3/11	2/6	1/5	1/3	50/115
Novosibirskiye islands	1/5	2/6	3/9	4/12	5/14	11/24	17/25	14/25	7/20	3/8	2/8	1/7	70/99

Note: mean - in the numerator, maximum days with fogs - in the denominator.

2.3. Continental run-off

In this section there were used monographs [*Antonov 1967; Domanitsky et al. 1971; The northern Yakutiya 1962; Soviet Arctic 1970*] and handbooks: The State Water Cadastre. Annual data on the regime and resources of the surface land waters and Resources of the surface waters of the USSR. Main hydrological characteristics.

One of the features of the Laptev Sea is a sufficiently strong continental run-off. The river run-off to the sea is about 767 cu. km [*Ivanov 1976*].

Fig.2.5 presents the distribution of mean multiyear volume of the run-off of the five main rivers and the contribution of each river to the total run-off is well evident.

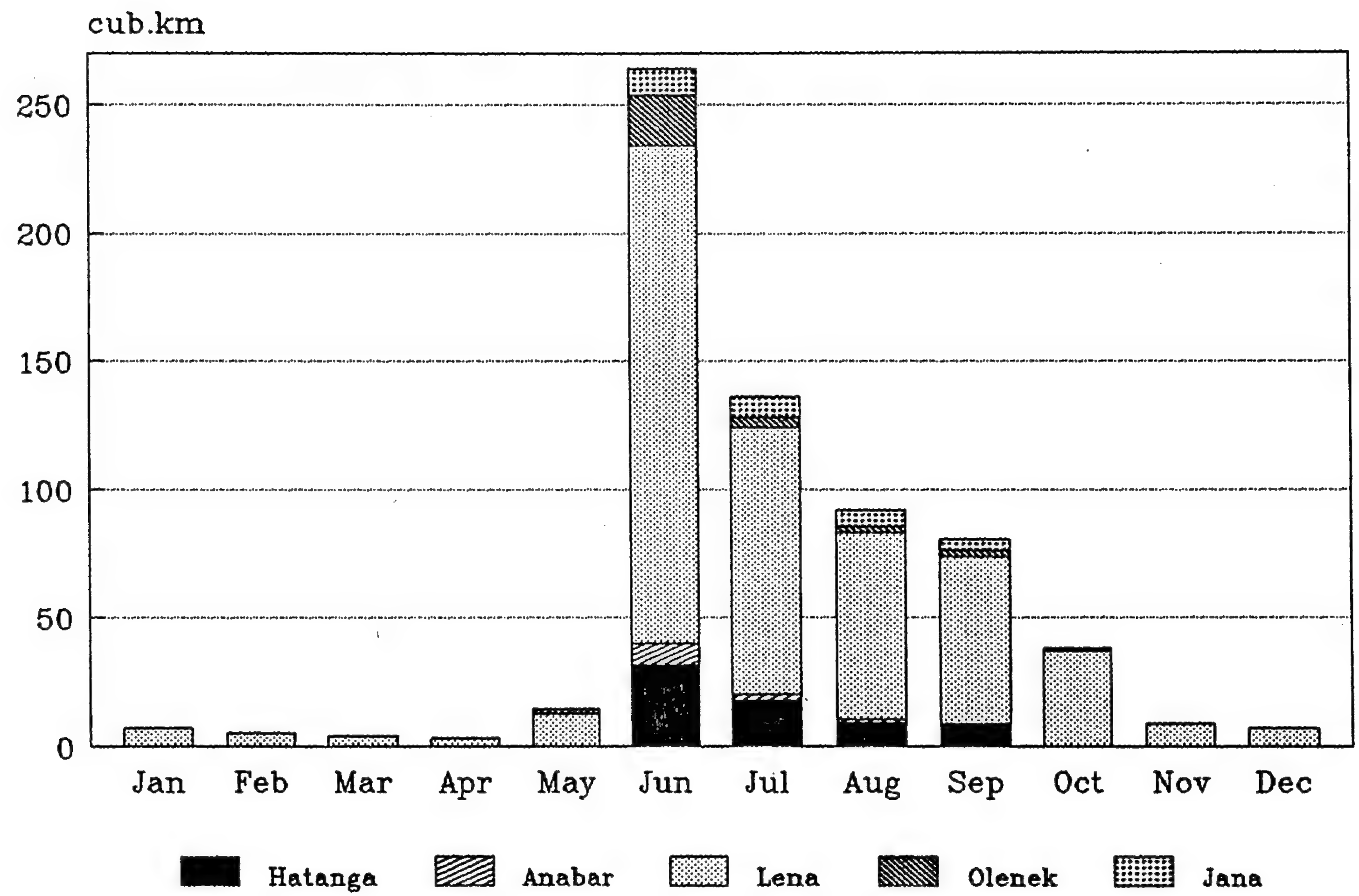


Fig. 2.5. Distribution of mean multiyear volume of the river run-off to the Laptev Sea.

1. The Khatanga river forms at the confluence of the Kotui and Kheta rivers, its length is 227 km. The area of the water catchment basin is 364 000 sq. km, it includes about 112 000 lakes, the density of the river network is 0.45 km/sq. km. The river alimentation is mainly due to snow. When falling into the Laptev Sea it forms an estuary.

The water discharge is measured at the gauging section of the river (p. Khatanga) from 1961. Mean water discharge is 3320 cu.m/s, maximum - up to 183000 cu.m/s. The diagram of mean multiyear discharges is given in Fig.2.6. During June almost half of the run-off volume is transported (Fig.2.7). The wave height of the flood is up to 8.5 m. Mean annual discharge is about 100 cu.km.

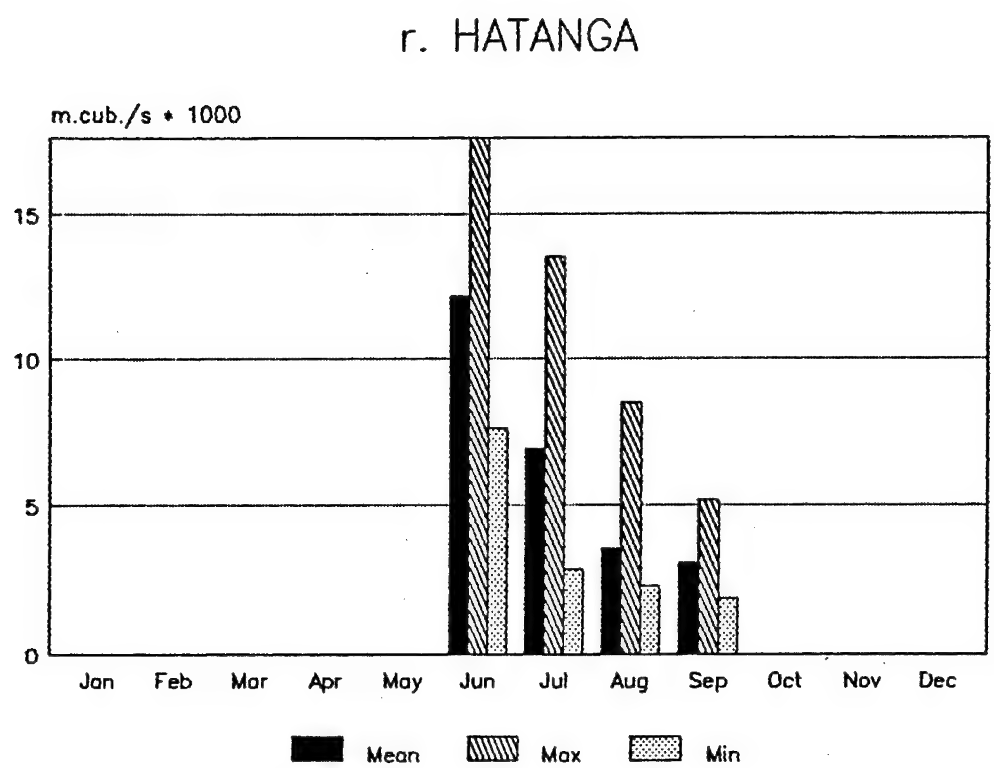
The Khatanga freezes in latė September - first half of October and it freezes down to the bottom from mid-December to May. The ice break-up is in the first half of June.

2. The Anabar river is 939 km long with an area of the water catchment basin 100 000 sq. km. When falling into the sea it forms a long shallow water estuary. The river alimentation is by snow and rain. There are many lakes at the territory of the water catchment basin.

The water discharge is measured at the gauging section of the river (p. Saskylakh) from 1954. Mean water discharge is 498 cu.m/s, maximum - up to 5000 cu.m/s. The diagram of mean multiyear discharges is given in Fig. 2.6. During June almost 64% of the run-off volume is transported (Fig.2.7). The value of mean annual run-off is about 15 cu.km.

The Anabar freezes in late September and freezes down to the bottom from mid-December to May. The ice break-up is in early June.

3. The Lena river is the second river in Russia by the stream- flow rate and the largest one in the Laptev Sea basin. Its length is 4400 km, the water catchment area is 490 000 sq. km. Much of the basin is in the area of multiyear frozen mountainous rocks and soils. There are many rivers. When falling into the sea Lena forms a vast delta, including up to 150 branches, the delta area is about 30 000 sq. km. The largest streams of the delta are Trofimovskaya (up to 70% of the river



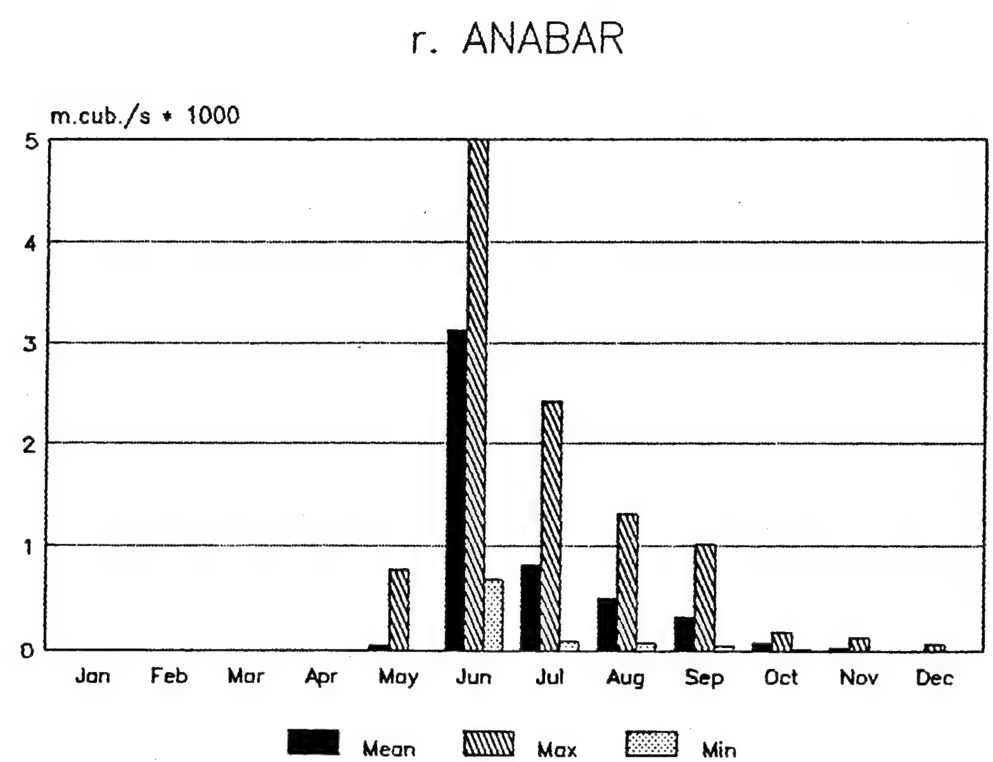


Fig. 2.6. Diagram of mean multiyear water discharges of the rivers Khatanga and Anabar.

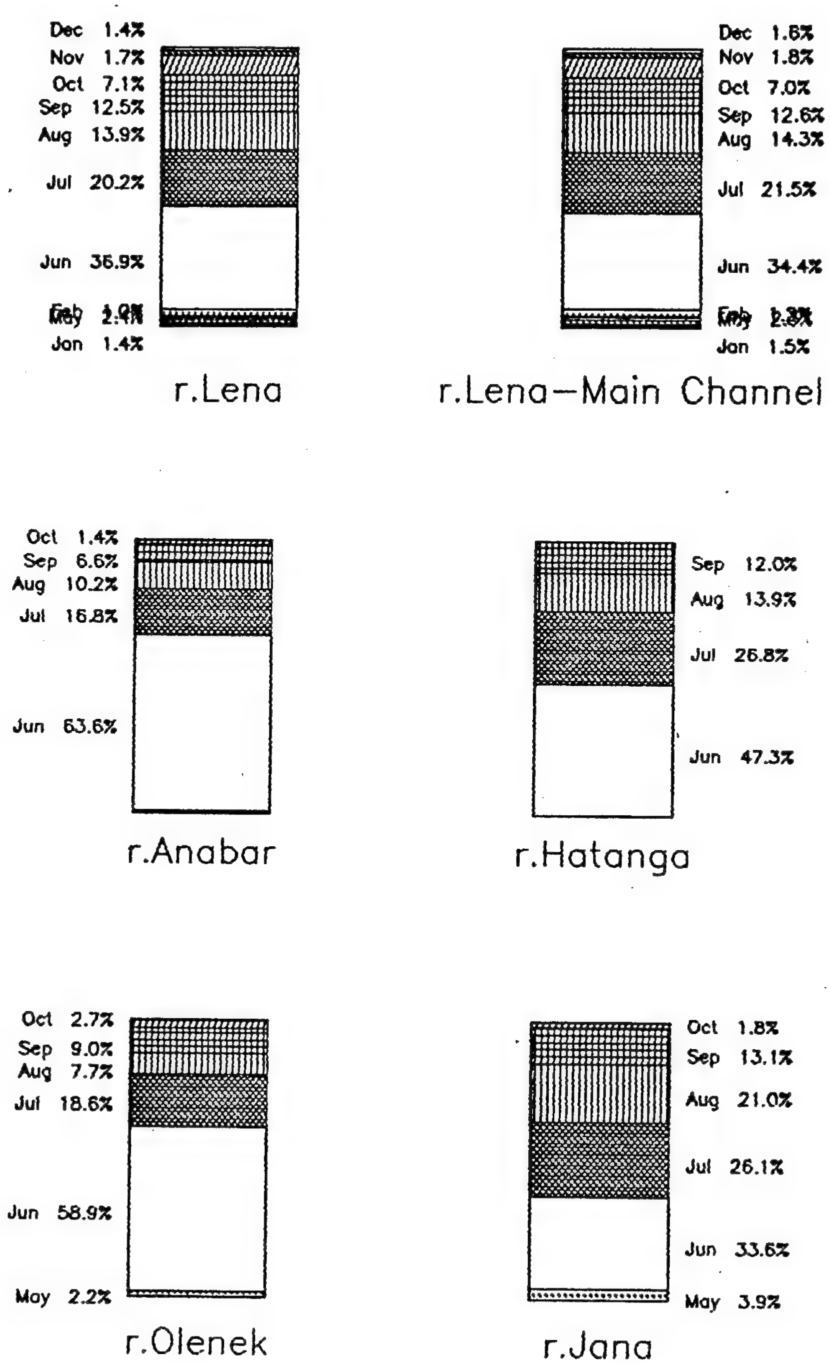


Fig. 2.7. A percentage distribution of the mean multiyear water discharge of the rivers of the Laptev Sea.

water run-off), Bykovskaya and Olenekskaya. The main river alimentation is due to snow (up to 50%) and rain. The ground water alimentation is 1-2%.

The Lena is characterized by a high spring flood (up to 18 m in the lower reaches), summer rain floods, a small run-off in winter.

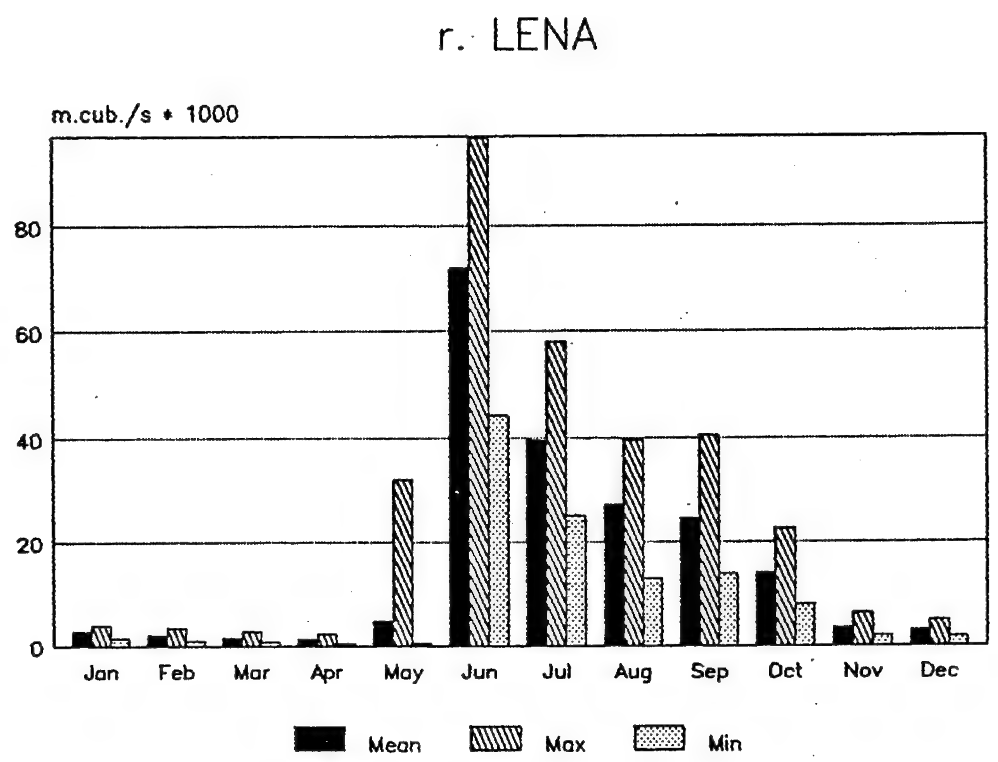
Water discharge is measured in the lower reaches (p. Kyusyur) from 1935. Mean water discharge is up to 17000 cu.m/s, maximum - up to 200 000 cu.m/s. At the delta top at the polar station Stolb water discharge is measured in the so-called Main Stream. Diagrams of mean multiyear discharges of Lena (p.Kyusyur) and in the Main stream (p.Stolb) are given in Fig.2.8. Fig.2.7 presents a percentage ratio of mean monthly water discharges. About 74% of mean multiyear run-off volume at the Kyusyur st. and about 85% of the run-off at the Stolb st. (Main Stream) are transported during June-September. Mean annual run-off of Lena is about 550 cu.km. The Lena river discharges on an average during the year are about 12 mln. t of suspended sediment and 41 mln. t of dissolved substances.

Ice becomes stable in the upper course from late October, in the lower one - from late September-early October. The break-up extends up to mid-May in the upper course and up to early June - in the lower reaches.

Fig. 2.9 presents diagrams of the variability of mean annual and mean monthly (June) Lena river discharges. Some periodicity in the fluctuations of the discharge value is observed and a well-pronounced period of about 8 years and a less-pronounced period of about 13.5 years are found out.

4. The Olenek river is 2292 km long with an area of the water catchnment basin of 220 000 sq. km. When falling into the sea it forms delta with an area of 475 sq. km and 20 km long. The river alimentation is due to snow and rain. The spring flood lasts from June to September and from October to May there is low water. The river freezes in late September - October. It breaks up in late May- first half of June. In some years in winter it freezes down to the bottom.

Water discharge is measureed at the gauging section (the Pur river mouth) from 1964. Mean water discharge is 943 cu.m/s,



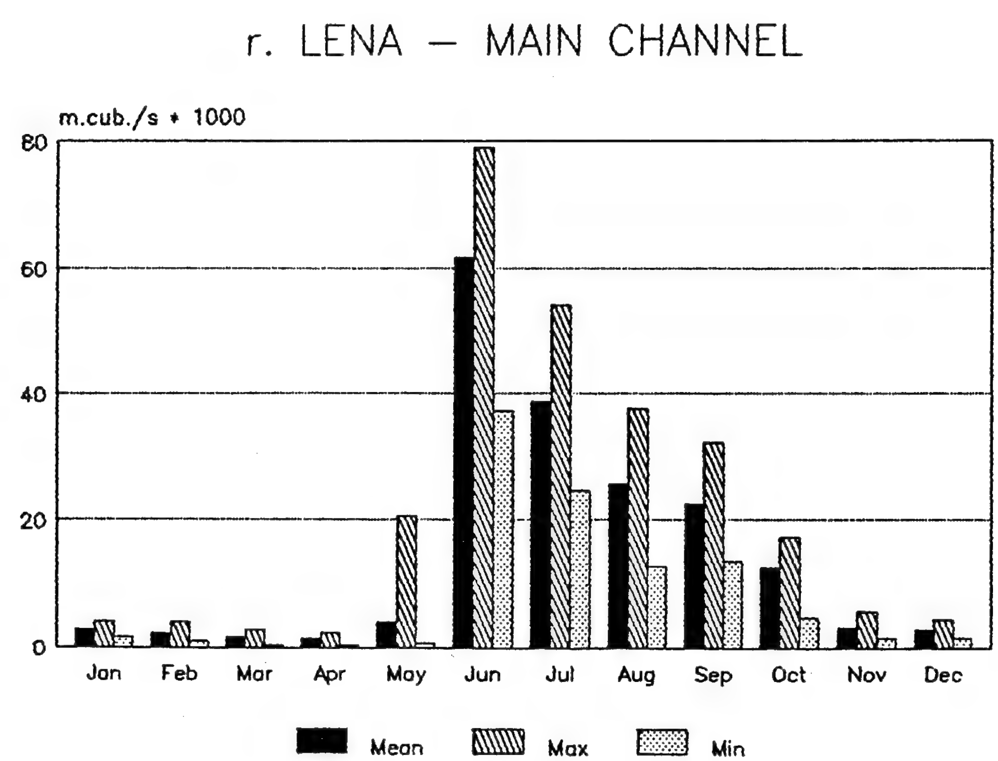


Fig. 2.8. Diagram of mean multiyear water discharges of the Lena river and the Main stream of the Lena river.

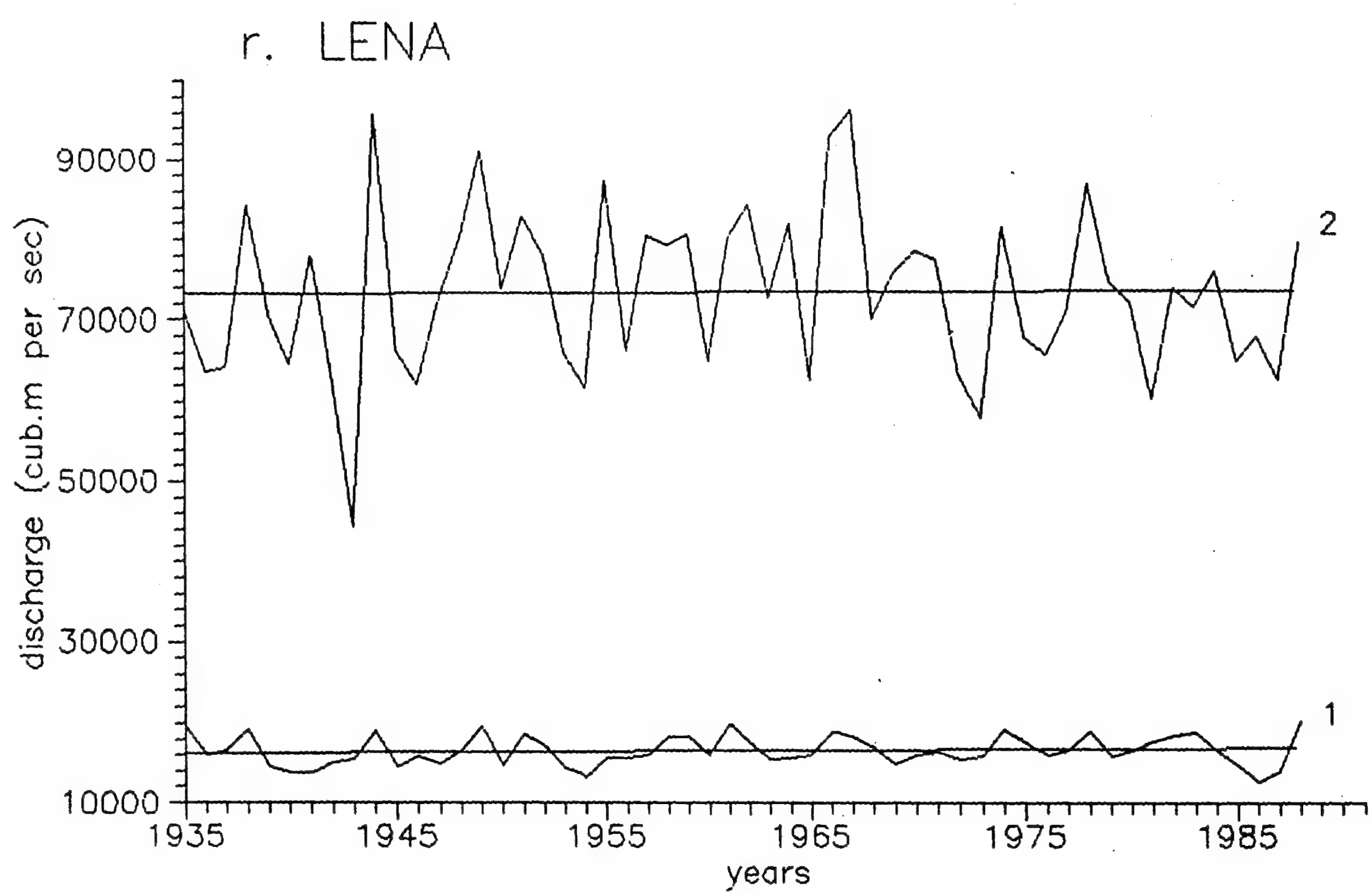


Fig. 2.9. Diagram of the variability of mean annual (1) and mean monthly June (2) discharges of Lena.

maximum - up to 11300 cu.m/s. The diagram of mean multiyear discharges is given in Fig.2.10. Almost 60% of the run-off volume is transported during June (Fig.2.7). Mean annual run-off is about 40 cu.km.

5. The Yana river is 872 km long with an area of the water catchment basin of 238 000 sq. km. When falling into the sea it forms delta with an area of 10200 sq. km. There are about 40 000 lakes at the basin territory. The river alimentation is due to snow and rain. In winter the river freezes down to the bottom for 2.5-3.5 months. Almost 85% of the river run-off is transported during May-June (Fig.2.7). The wave height during the spring flood is up to 12 m.

Water discharge is measured at the gauging section (p. Yubileynaya) from 1972. Mean water discharge is 974 cu. m/s, maximum - up to 7900 cu.m/s. The diagram of mean multiyear discharges is given in Fig.2.10. Mean annual discharge is about 40 cu.km.

The Yana freezes in October and breaks up in the second half of May - first half of June. Near Verkhoyansk in winter Yana freezes down to the bottom for 2.5-3.5 months.

Depending on the volume of the water brought by the rivers and the hydrometeorological situation the river waters extend to the north-east, reaching the northern tip of the Kotel'ny island (Fig.2.11.a), northward to latitude 77^0 (Fig.2.11.b) or farther to the east, outflowing through the straits of the East-Siberian Sea (Fig.2.11.c) [*Soviet Arctic 1970*].

2.4. Water masses and thermohaline structure

A large continental ouflow, a free water exchange with the Arctic Ocean and perennial ice over a considerable area of the Laptev Sea are considered to be the main factors for the formation of water masses.

Table 2.4 presents correlation coefficients between the inflow of the Pacific and the Atlantic waters and the Lena river run-off and the surface water salinity of the Laptev Sea [*Nikiforov, Shpaikher 1980*]. It follows from Table 2.4 that all these three factors significantly affect the formation of the

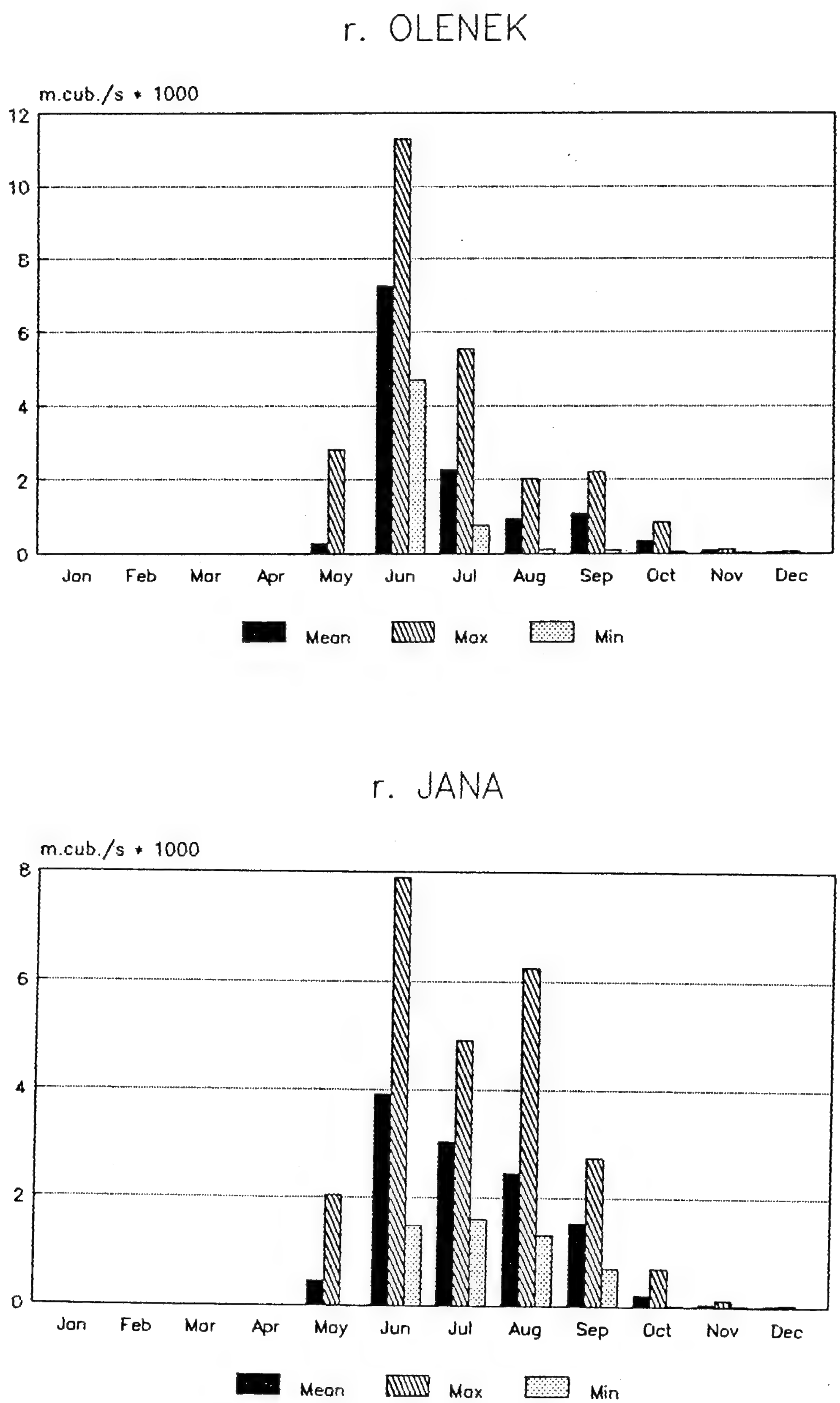


Fig. 2.10. Diagram of mean multiyear water discharges of the rivers Olenek and Yana.

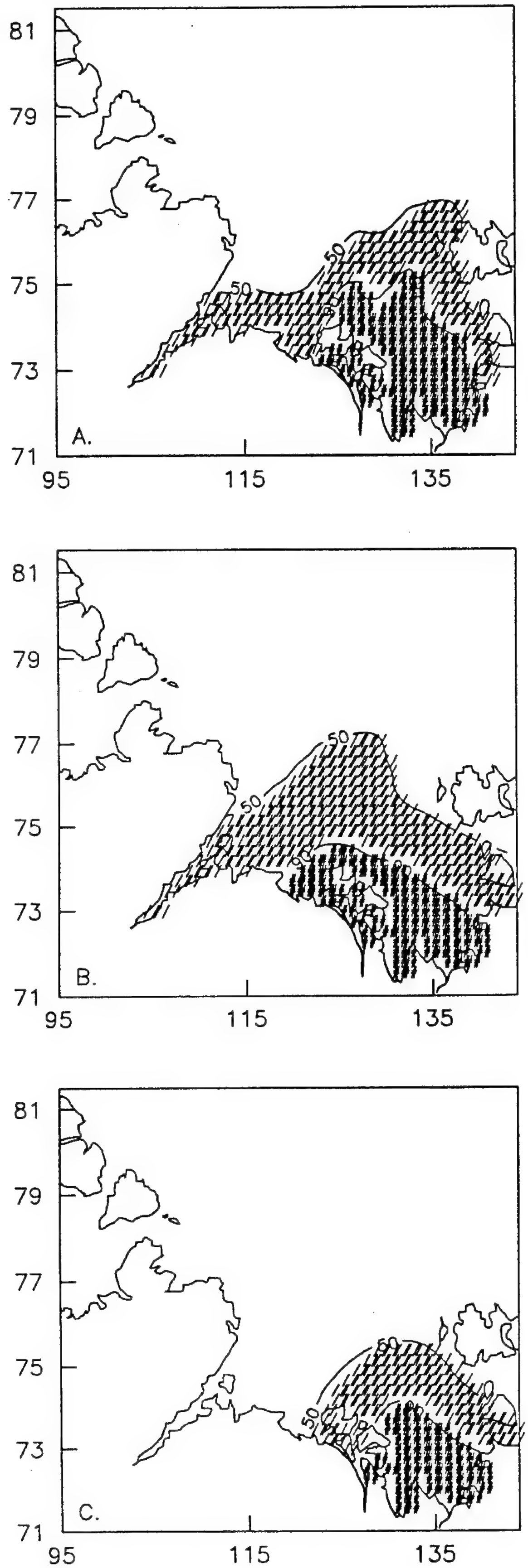


Fig. 2.11. Types of the river water distribution, %

a - northern maximum
b - northern minimum
c - eastern
[Soviet Arctic 1970]

water masses of the Laptev Sea.

Table 2.4

Correlation coefficients between the inflow and salinity of the surface waters into the Laptev Sea

Salinity	Western part of the sea			Eastern part of the sea		
	Atlantic Water's Inflow	Pacific Water's Inflow	Lena's Run-off	Atlantic Water's Inflow	Pacific Water's Inflow	Lena's Run-off
in synchronous way	0.40	-0.50	0.60	-0.11	-0.45	0.31
in a year	0.39	-0.65	0.35	0.17	-0.41	0.22
in a 2 years	0.57	-0.69	0.24	0.18	-0.37	0.35
in a 3 years	0.78	-0.48	0.26	0.27	-0.06	0.43
in a 4 years	0.57	-0.10	0.30	-0.09	0.35	0.54
in a 5 years		0.03			0.66	

The characteristics of the water masses of the Laptev Sea are given in Table 2.5 [*Nikiforov, Shpaikher 1980*], and the areals of their extent in the summer and winter periods are presented in Fig.2.12 [*Dobrovolskiy, Zalogin 1982*]. In the Laptev Sea the surface water of the Arctic Basin and the surface water of the Laptev Sea, which have a weak seasonal variability, prevail. Warm Atlantic water is spread in the north in the deep water troughs under the surface Arctic water. The depths below 800-1000 m are occupied by a cold bottom water with a temperature of -0.4^0 - -0.9^0 C and salinity of 34.90-34.95 $^0/_{00}$. Its formation is related with the sinking of cooled sea water by the continental slope down to large depths. A decisive role in the formation of water masses in the summertime belongs to the processes, occurring in surface water and to zones of their mixing with river waters. In the coastal zone under the effect of

Table 2.5

Main characteristics of the water masses of the Laptev Sea

	Water masses	Surface Water of Arctic Basin	Surface Water of Laptev Sea	Summer Water of Laptev Sea	River's Water	Atlantic Water
Winter	Temperature ^0C	-1.80	-1.40	---	---	2.25
Winter	Salinity $^0/_{00}$	32.00	25.00	---	---	34.98
Summer	Temperature ^0C	-1.80	-1.40	6.80	11.70	2.25
Summer	Salinity $^0/_{00}$	32.00	22.00	32.00	0.50	34.98

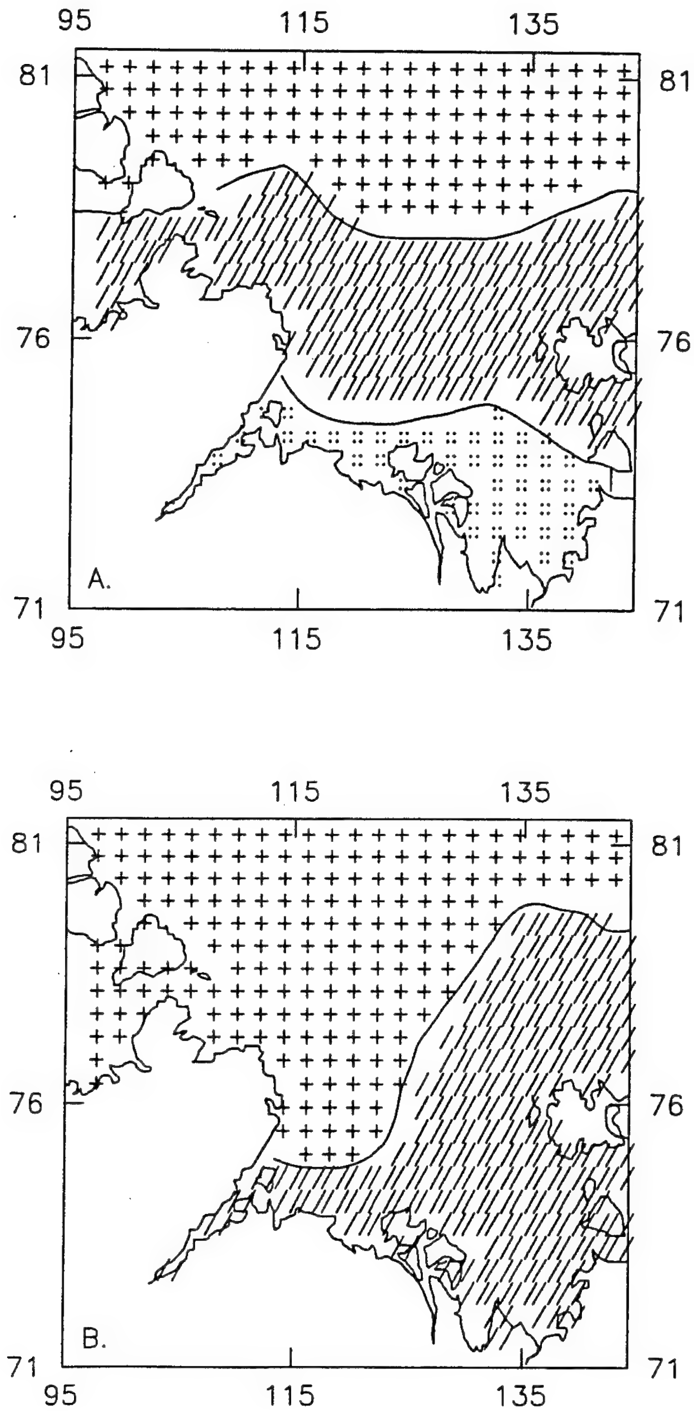


Fig.2.12. Distribution of water masses in the surface layer in the summer (a) and winter (b) periods

:: :: - river water

// // - surface water of the Laptev Sea

+ + + - surface water of the Arctic Basin

[Nikiforov, Shpaikher 1980]

the river run-off the water temperature in summer can reach 10-12^0 C with the salinity decrease up to 0.3-1 $^0/_{00}$.

Fig. 2.13 presents a characteristic spatial structure of temperature and salinity at the surface of the Laptev Sea in the summertime. The main feature of the temperature and salinity fields appears to be the presence of large gradients of these characteristics in the zones of mixing of river and sea water and a comparatively uniforn water structure in the northern sea. In the wintertime due to a sharp decrease of the run-off, ice cover formation and end of convection processes, the thermohaline sea structure is relatively homogenous (Fig.2.14). The water temperature varies from -1.4^0 in the eastern sea up to -1.8^0 in the north-western part. The water salinity in the south-western sea has the values of 22 - 24 $^0/_{00}$, smoothly increasing northward and to the north-west up to 32 - 34 $^0/_{00}$.

Fig. 2.15 presents vertical temperature and salinity profiles for the western, south-eastern and northern regions of the Laptev Sea in the summertime. In summer the upper layer 10-15 m thick is warmed and has a temperature of 5^0 - 7^0 in the south-eastern part and 1^0 - -1^0 in the northern and western parts of the area.

In winter a vertical temperature and salinity distribution in the shallow area is quite uniform, the salinity weakly increasing with depth and the temperature being within -0.5^0 -1.9^0 C, depending on the region (Fig.2.16). In the deep northern Laptev Sea a temperature maximum is observed at a level of 100-400 m, the salinity dramatically increases from the surface to a 100 m level from 29 to 33-34.5$^0/_{00}$ and practically does not change further with depth.

A complicated vertical structure of the water masses is sometimes observed in the coastal zone of the contact of river and sea water.

2.5. Hydrochemical regime of the Laptev Sea

The sea is shallow, well-stratified, with well-pronounced layers at small depths. The river run-off plays a significant

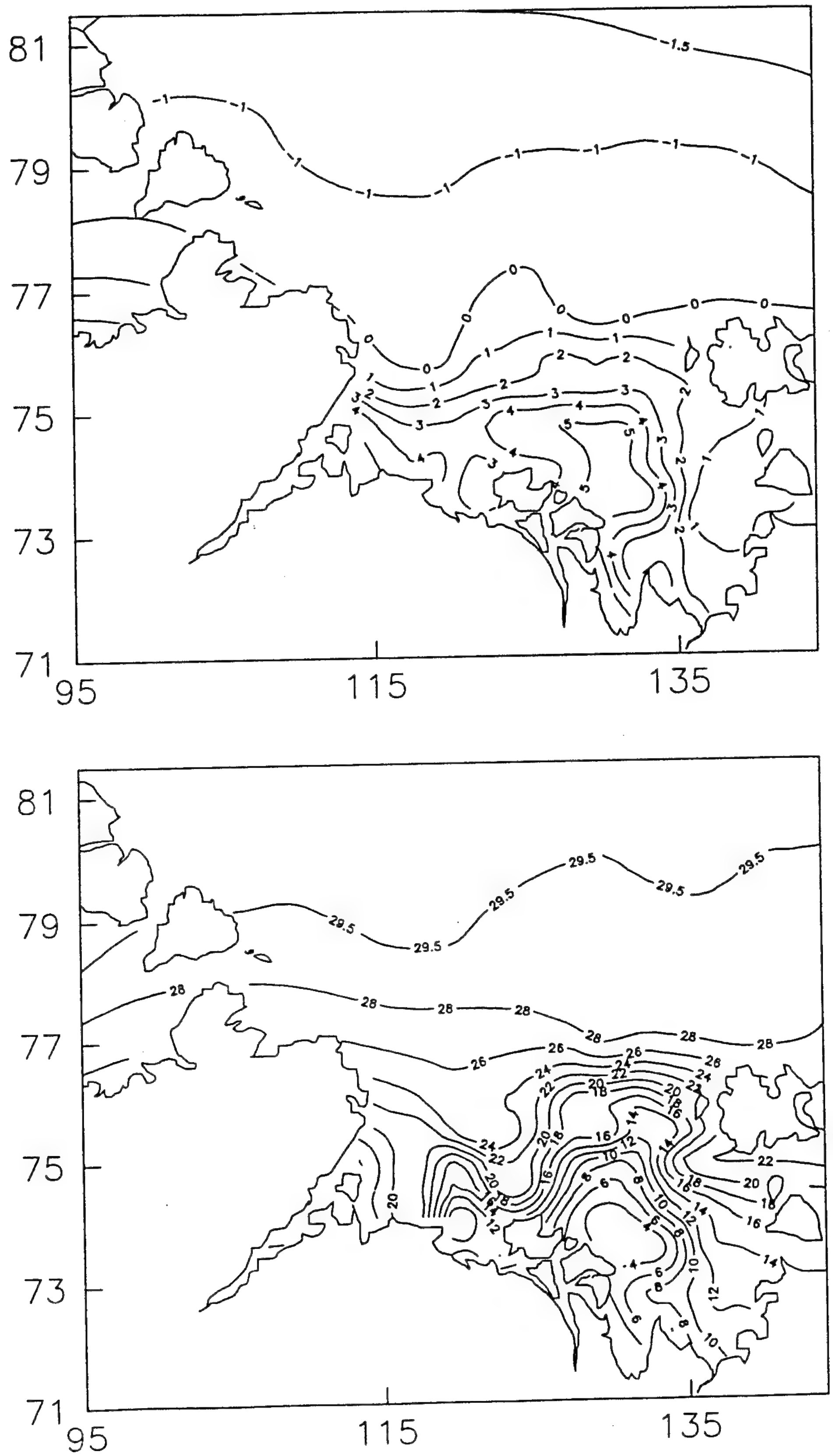


Fig. 2.13. Tipical distributions of the water temperature (a) and salinity (b) at the surface of the Laptev Sea in summer [Dobrovol'skiy, Zalogin 1982]

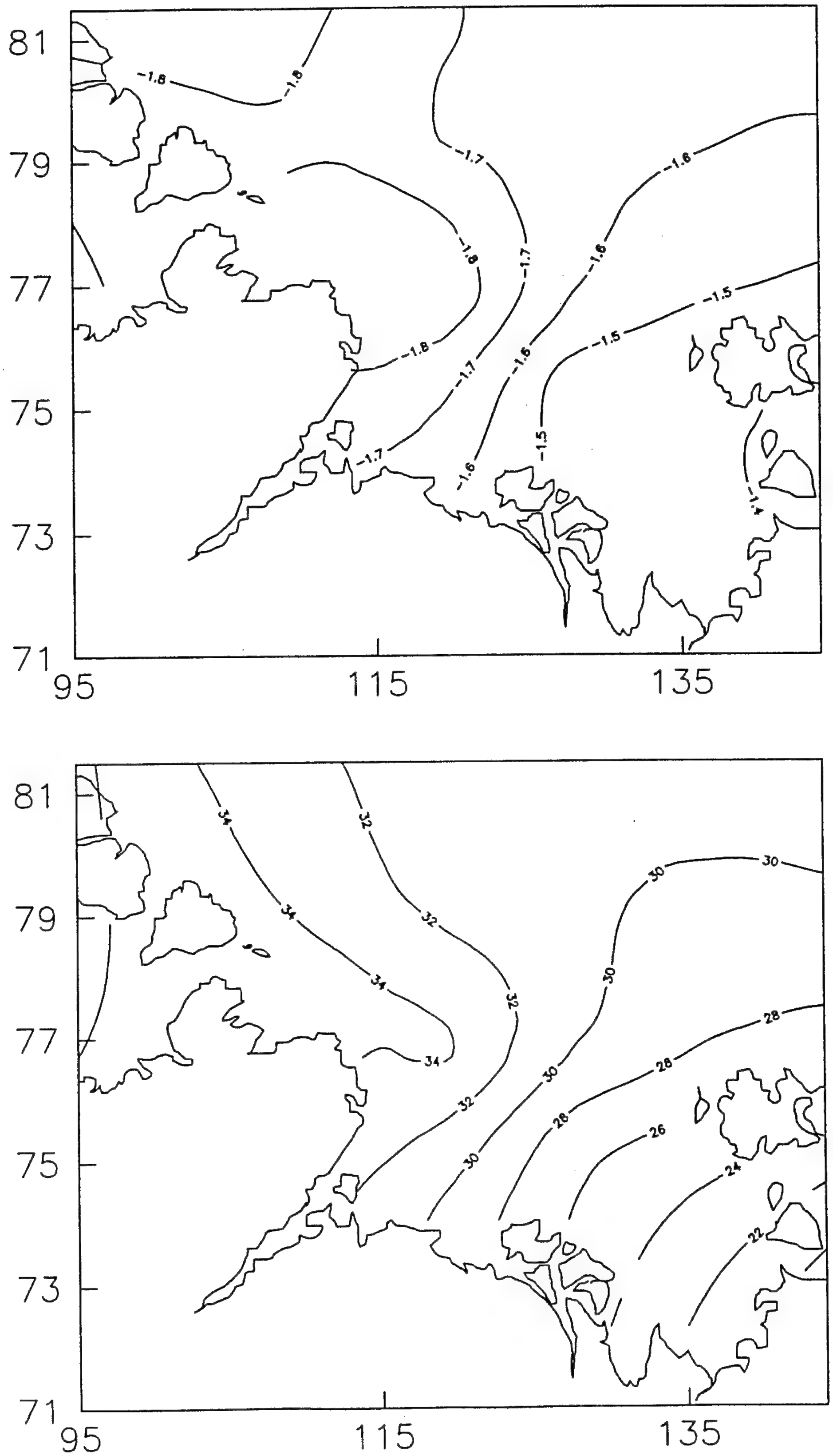


Fig. 2.14. Tipical distributions of the water temperature (a) and salinity (b) at the surface of the Laptev Sea in winter [Dobrovol'skiy, Zalogin 1982]

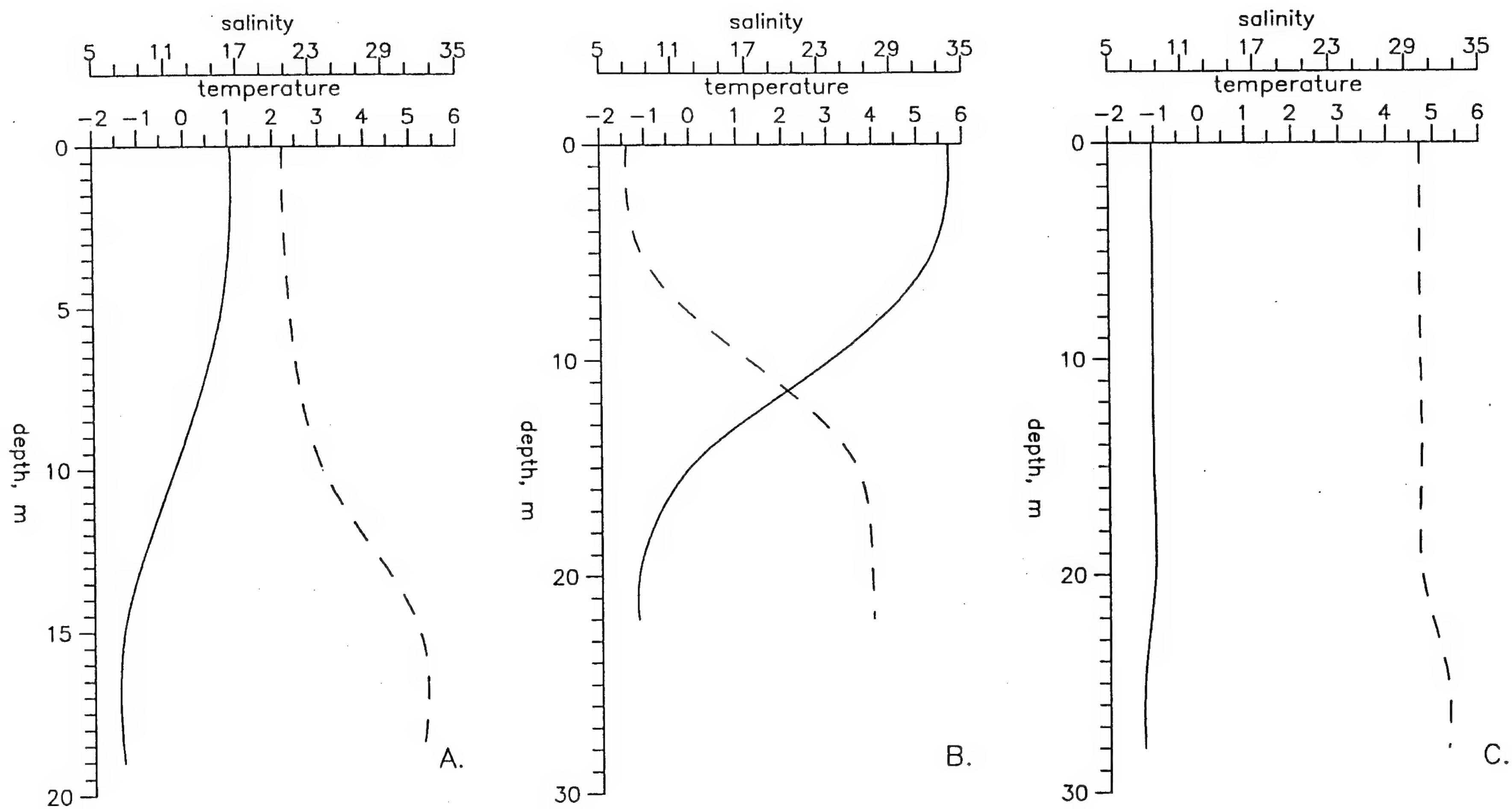


Fig.2.15. Vertical water temperature and salinity profiles in summer in different parts of the Laptev Sea.
a - south-eastern, b - northern, c - south-western part

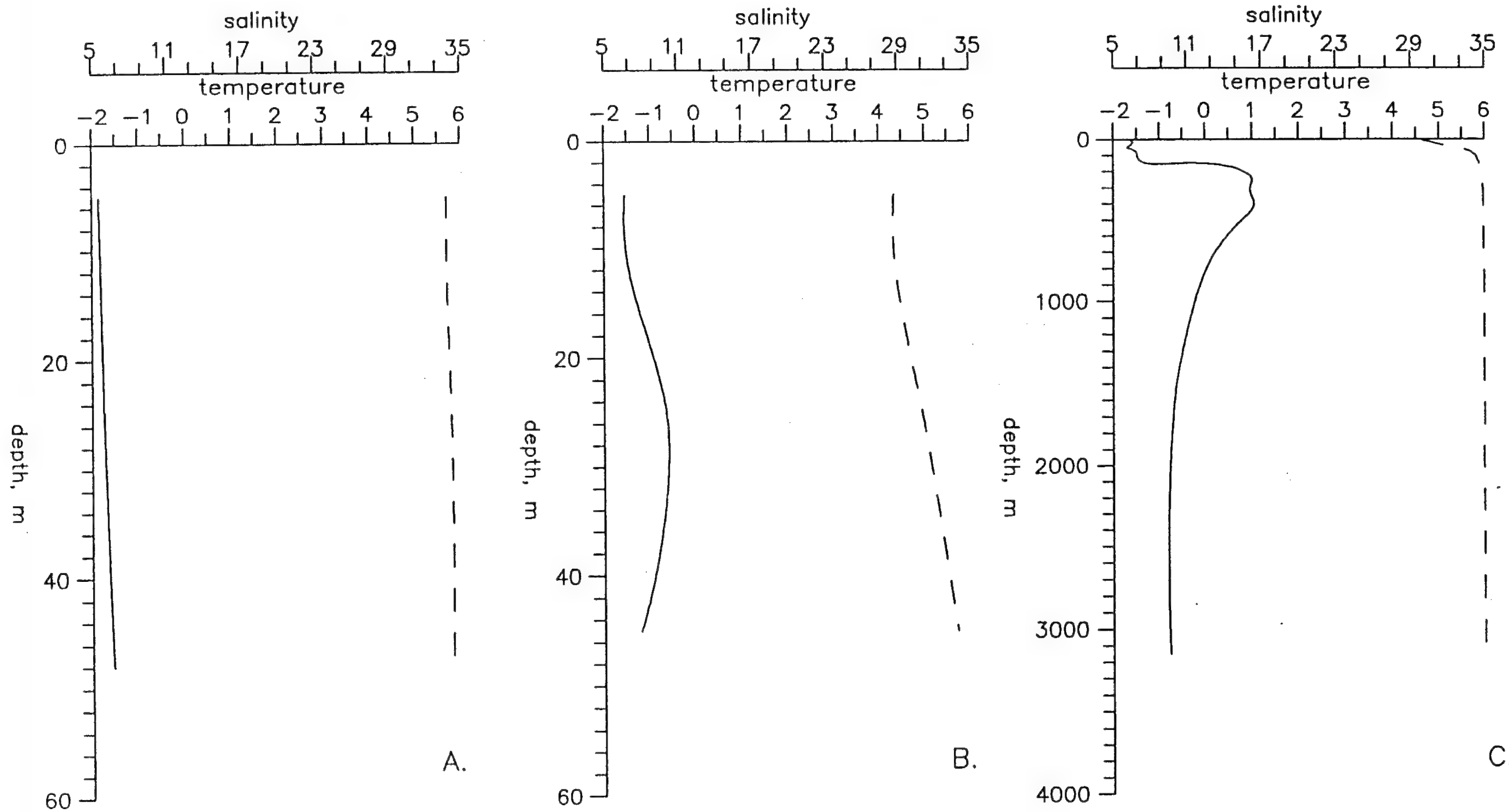


Fig.2.16. Vertical water temperature and salinity profiles in winter in different parts of the Laptev Sea.
a - south-eastern, b - northern, c - south-western part

role in the formation of the hydrochemical structure. The zone of the river run-off influence during summer is characterized by lower values of dissolved oxygen in the surface layer (Fig.2.17). Undersaturation is , as a rule, 1-3%. At the same time in the western sea half, where surface water inflows from the Arctic basin and off the drifting ice edge there is a 10-15 % supersaturation of the surface layer with oxygen.

The Laptev Sea is usually divided into four parts by the vertical distribution features. In the south-east of the sea large gradients of the oxygen concentration change by vertical are observed, particularly in the pycnocline. In the south-western sea the drop of oxygen values with depth does not occur so dramatically, since the influence of the Khatanga and Anabar rivers is much less than of the Lena river. One of the features of this region is the presence of a subsurface maximum of the oxygen concentration in the layer of the largest temperature gradients. In the fall the maximum disappears and the oxygen concentrations throughout the entire thickness of the convective mixing layer become equal.

The north-western sea is characterized by an increase of the oxygen concentration in the layer of 35-40 m. formed under the effect of surface Arctic water.

In the north-east of the sea the oxygen distribution by vertical is governed by the effect of the river run-off and water exchange with the Arctic basin, which leads to a sharper layering of the water thickness.

Almost over the entire eastern sea region there is a significant deficit of dissolved oxygen in the near-bottom layers, reaching 40-50%. In the Buor-Khaya Gulf in shallow bottom depressions the absence of dissolved oxygen and the presence of hydrogen sulphide at the near-bottom levels were recorded in the wintertime [*Sidorov, Gukov 1992*]. Stagnant water with a large oxygen deficit at the near-bottom levels is also observed in the bottom depressions in Yana Bay. It flows along the troughs northward, occupying the position in the water thickness according to its density and forms layers with a minimum oxygen supply at intermediate depths in the central and north-eastern sea regions.

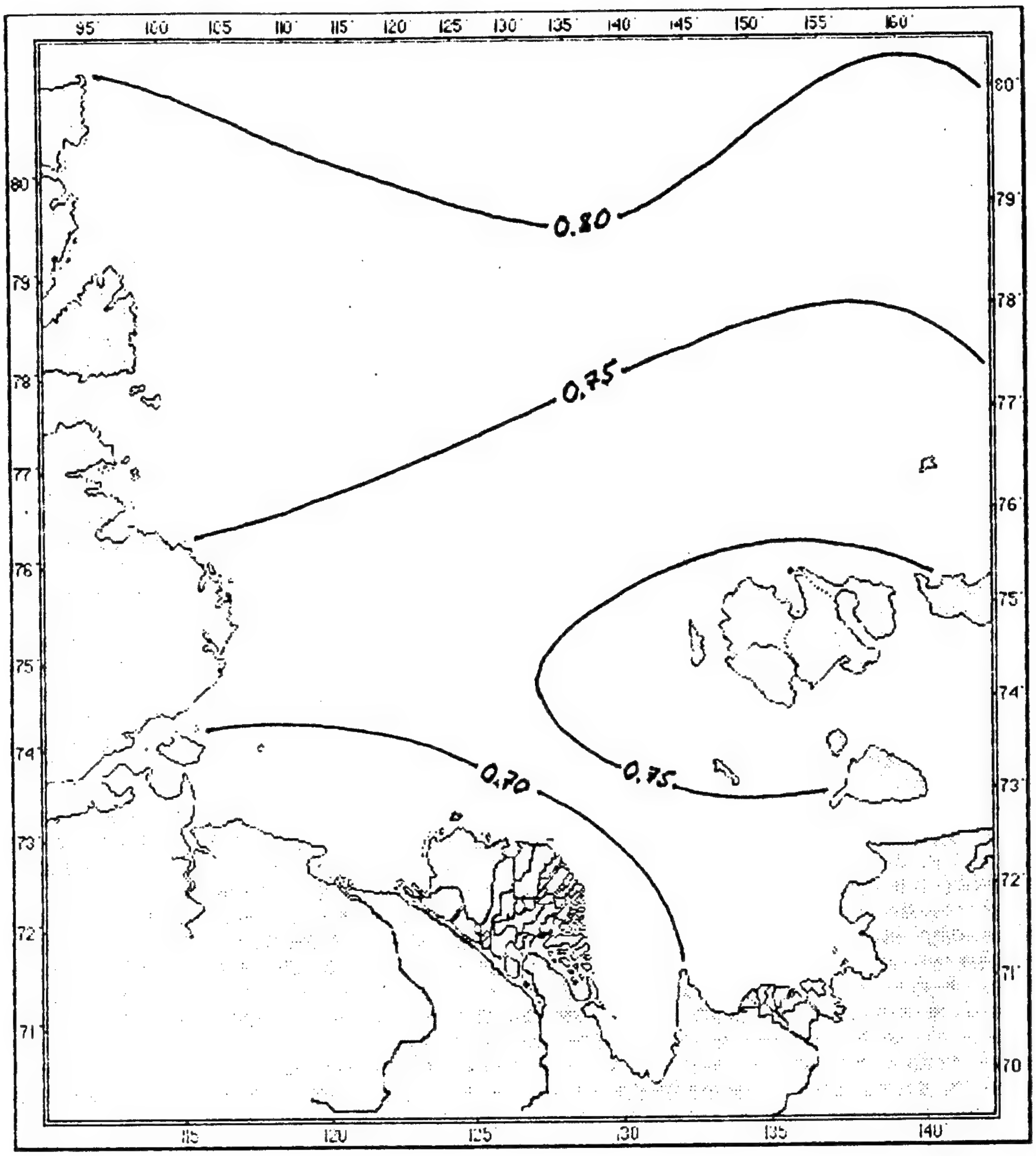


Fig.2.17. Mean distribution of the dissolved oxygen (mg-a/l) for the observation period in the surface water of the Laptev Sea [Rusanov et al. 1979]

The Lena river is the main source of silicon in the Laptev Sea as its share constitutes almost 70% of the entire river run-off in the sea, and also due to the high levels of silicates in river water, reaching 120-130 μMol/l during winter low water and in the beginning of the spring flood. Also, there is a mass death and dissolution of river phytoplankton, containing silicon, in the region of the hydrological front. That is why, in the region, adjacent to Bykovsky stream of the Lena river, maximum silicon concentration in the surface layer (more than 150 μMol/l) is observed. With the spreading of river water and its transformation a gradual decrease of the silicon concentration in the surface layer takes place, mainly due to mixing with ambient water and silicon consumption by sea diatoms (Fig. 2.18). Mean silicon concentration in the regions of the Arctic Ocean, adjacent to the Laptev Sea is less than 10 μMol/l, decreasing in summer to zero values.

During summer the change of silicon content in surface water of the central and eastern sea regions is about 20 μMol/l, being 3-5 μMol/l in the northern and western regions.

At favourable hydrometeorological conditions the effect of river water by the end of the summer period extends almost over the entire sea area. In the west the river effect is traced to the Northern Land islands, where in the surface layer there is an interaction with water masses, desalinated by the run-off of the Ob' and Yenisey rivers, incoming through Vil'kitsky strait from the Kara Sea.

The north-eastern type of the river water spreading, at which enhanced silicon concentrations in the surface layer are found north of the East-Siberian islands, is observed most often.

There are several types of the vertical distribution of silicon in the Laptev Sea. In the regions, subjected to the effect of the river run-off, its concentration decreases with depth. There is a layer of minimum silicon concentration at a depth of 10-15 m, beneath which the silicon concentration increases up to 20-30 μMol/l.

The western sea regions are characterized by the increase of the silicon concentration with depth. At the near-bottom levels in these regions the content of silicates is 10-15 μMol/l.

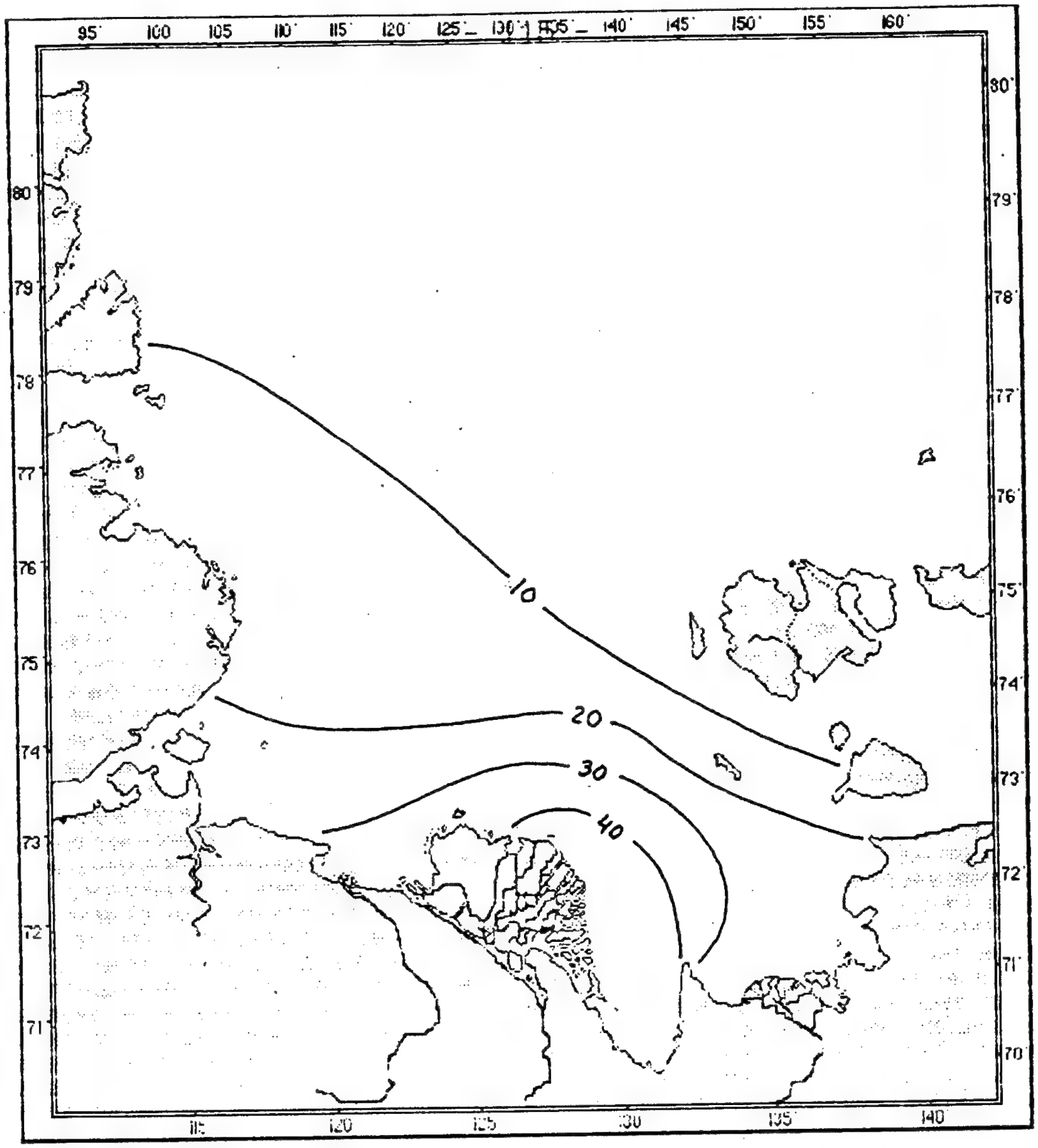


Fig.2.18. Mean distribution of the silicate concentration (μMol/l) for the observation period in the surface water of the Laptev Sea [Rusanov et al. 1979]

In the northern sea in summer the entire water column is usually poor in nutrients. Only when intermediate Pacific water flows onto the shelf from the Arctic Basin, the concentration of nutrients sharply increases.

The phosphates and nitrates are actually absent in summer in the surface layer of the Laptev Sea. In the regions, adjacent to the mouths of large rivers, the concentration of phosphates and nitrates is much higher, being 0.3-0.5 μMol/l. With depth the level of these elements increases everywhere. The concentration of phosphates in the near-bottom layers is 1.0-1.5 μMol/l, and of nitrates - 7-10 μMol/l.

2.6. Wind-induced waves in the Laptev Sea

The dimensions of the waves in the Laptev Sea for one and the same wind speed of a constant direction depend on the dimensions of the open water area, where they appear and develop. The wave fetch varies from 50 miles in July up to 300-350 miles in September, and the maximum fetches can reach 450-500 miles. The waves more than 3 m high are most often observed in September [*Wind and Waves in the Oceans and Seas 1974*].

The most intensive waves develop off the western shores and in the central sea . The waves less than 1.5 m high are most frequent. In summer (July-August) when the central and south-eastern sea become ice free the maximum wave heights can reach 5 m in the central sea during the east storm winds. In the south-eastern sea during storm winds by the fetch conditions the wave heights do not exceed 4 m at a wind speed of 18-20 m/s. The fall period in the Laptev Sea is most stormy and at this time the wave height reaches its maximum of 6 m. Table 2.6 presents data on the occurrence frequency of the waves by the wave height gradations for the central sea [*Wind and Waves in the Oceans and Seas 1974*].

2.7. Water exchange

The water balance of the Laptev Sea is composed of its water exchange through the straits and open sea boundaries with the

Table 2.6

Occurrence frequency of the waves for the Laptev Sea

Navigation period	Prevailing direction	Occurrence frequency of the waves, % at the wave height, m				Wave elements		
		0-3	3-5	5-7	>7	Highest height m	Length m	Period sec
VII	NE и E nonstability	96	3.5	0.5	0	5.8	104	8.3
VIII	NE и E nonstability	93	6	1	0			
IX	From SW in eastern part to S & SE in northern nonstability	90	8	2	0			
X	From SW in southern part to SE in northern	95	4.5	0.5	0			

adjacent oceanic and sea areas, river run-off, evaporation and precipitation.

The average annual volume of the river run-off into the Laptev Sea is about 600 cu.km or about 0.02 Sv.The amount of precipitation (20-30 cm a year) is a little more than the annual evaporation volume.

An approximate estimate of the water exchange with the Kara, East-Siberian Seas, and the Arctic Basin are given in Table 2.7. [*Shpaikher, Fedorova 1978*].

Table 2.7

Mean annual water exchange of the Laptev Sea

Inflow	Discharge		Outflow	Discharge	
	cu.km/year	Sv		cu.km/year	Sv
Kara Sea	$10.8 \cdot 10^3$	0.32	Kara Sea	$7.2 \cdot 10^3$	0.22
East-Siberian Sea	$3.24 \cdot 10^3$	0.10	East-Siberian Sea	$3.24 \cdot 10^3$	0.10
Arctic Basin	$17.6 \cdot 10^3$	0.53	Arctic Basin	$21.5 \cdot 10^3$	0.65

One should note an approximate character of the estimates given in connection with a significant interannual, interseasonal and intraseasonal variability of the water flows through the straits.

2.8. Water circulation of the Laptev Sea.

The characteristics of non-periodic currents of the Laptev Sea is given for the summertime (August-September) and for open water conditions, that is, at ice absence in the sea area under consideration.

The characteristics is made mainly on the basis of publications.

The currents of the Laptev Sea have not been sufficiently

well studied, particularly, in the western sea region, where heavy ice conditions prevent the studies.

Non-periodic currents of the Laptev Sea can be considered in the first approximation as a sum of two main components: permanent and wind-driven currents.

2.8.1. Permanent currents

Permanent currents do not depend on the wind, acting at a given time moment. The field of permanent currents forms under the effect of large-scale factors, the main of which for the Laptev Sea in summer are the following: location and intensity of the Icelandic Low and Arctic High of atmospheric pressure, water exchange with the Arctic Basin, as well as with the Kara and East-Siberian Seas, income of large masses of fresh water, exported by large rivers - the Lena, Khatanga, Yana, etc.

Due to their large relative stability in space and time, permanent currents form the basis of the water circulation of the sea, which produces a large influence on all processes, occurring in it.

The system of permanent currents in the surface layer of the Laptev Sea (Fig. 2.19) forms a sufficiently well-defined cyclonic water circulation [*Soviet Arctic 1970; Atlas of the Oceans. The Arctic Ocean 1980; Dobrovol'sky, Zalogin 1982*].

Along the mainland coast there is a coastal current from west to east. It is intensified by the Lena current in its eastern part (1). Much of it, approaching the New-Siberian Islands, is at first directed to the north-west, and then to the north and in the form of the New-Siberian current (2) merges with the Transarctic current (3), moving from east to west. In the vicinity of Northern Land the waters of the southern periphery of the Transarctic Current have a general direction southward and in the form of the East-Taimyrskoye Current (4) reach the coastal eastern flow, thus enclosing the cyclonic gyre of sea surface waters. Part of waters of the New-Siberian Current moves through Sannikov strait eastward into the East-Siberian Sea.

The speeds of the permanent currents of the Laptev Sea are small. Even in the ennumerated main flows they do not exceed 10 cm/s, being even weaker in the central sea region.

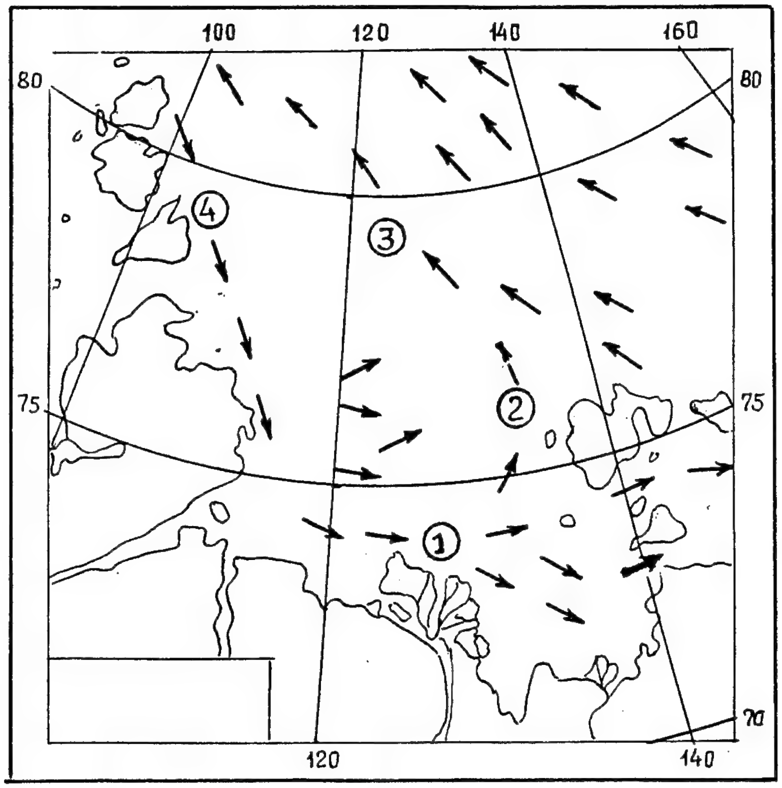


Fig.2.19. Scheme of surface water circulation of the Laptev Sea in summer.

Currents: 1 - Lena, 2 - New-Siberian
3 - Transarctic, 4 - East-Taimyrskoye.
[Dobrovol'skiy, Zalogin 1982]

Since the factors, governing the permanent currents of the Laptev Sea are exposed to long-term changes, then, correspondingly, the sea water circulation changes too. The most significant and comparatively well studied appear to be those, which are governed by the interannual shifts of the Icelandic Low and Arctic High of atmospheric pressure [*Gordiyenko, Karelin 1945; Soviet Arctic 1970; Shpaikher, Fedorova, Yankina 1972; Nikiforov, Shpaikher 1980*].

During the years, when the effect of the Icelandic Low is predominant in the Arctic (see Fig. 1.23.a), the water transport from west to east intensifies in the Arctic Seas. In the Laptev Sea the export of surface Arctic water to the East-Siberian Sea by the New-Siberian Currents increases. The center of the cyclonic water gyre is located in the middle of the northern Laptev Sea.

During the years of the predominant influence of the Arctic High of atmospheric pressure (see Fig. 1.23.b) there is a developed transport of water masses from south to north in the Arctic Seas. The outflow of river water in the Laptev Sea increases. The center of the cyclonic gyre shifts toward the Northern Land.

2.8.2. Wind-driven currents

Wind-driven currents are caused by the wind, acting at a given time moment, and change their direction and speed in accordance with the changes of wind and atmospheric pressure.

The analysis of field data by currents, carried out by Baskakov, and the results of dividing pressure fields into types over the area of the Laptev Sea, developed by Bakulin and Kuznetsov, showed that in summer in the south-eastern Laptev Sea there are formed fields of wind-induced surface currents, corresponding to the identified types of pressure fields.

Fig.2.20 shows the fields of wind-induced currents for two types of pressure situations: the first, at which western atmospheric transports prevail over the eastern Laptev Sea and the second, at which eastern transports dominate.

In the first case in the south-eastern sea region there is observed a cyclonic wind-induced gyre of surface water

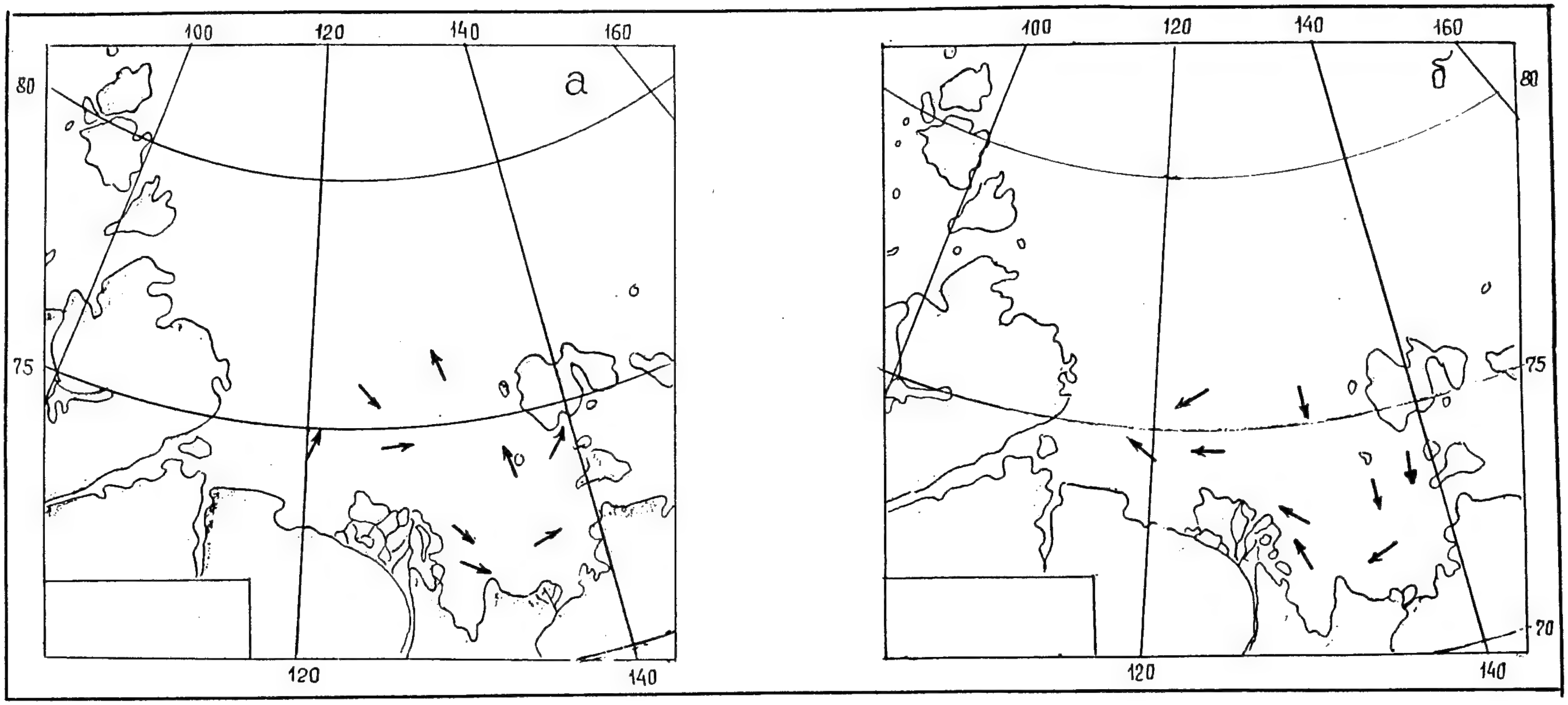


Fig. 2.20. Wind-driven surface currents in the south-eastern Laptev Sea at western (a) and eastern (b) atmospheric transports. [Baskakov 1986]

(Fig.2.20.a), while in the second case - an anticyclonic one (Fig.2.20.b).

The speeds of wind-induced currents at wind speeds from 5 to 10 m/s, prevailing here in summer, usually do not exceed 10 cm/s.

2.9. Tides

In the Laptev Sea the tide is well-pronounced and has a character of an irregular semi-diurnal wave. The tidal wave enters from the north and propagates to the shore, attenuating and deforming with the approach to it. A map of cotidal lines, obtained by means of modeling [*Proshutinsky 1993*], is given in Fig.2.21. The value of the tide is usually small, predominantly of about 0.5 m (Fig.2.22). Only in Khatanga Bay the amplitude of tidal level oscillations exceeds 2.0 m in the syzygy. The tidal wave, coming to Khatanga Bay, propagates almost to 500 km upstream the Khatanga river. This is one of the rare cases of such deep penetration of the tide to the river. And the bore phenomenon is not observed at the Khatanga. The tide almost does not enter other rivers, falling into the Laptev Sea and attenuating very close to the mouth, as these rivers have deltas, in the tributaries of which the tidal wave is damped.

2.10. Level regime of the Laptev Sea

Surge level fluctuations are observed at any time of the year, but most often in the fall at strong and stable winds. The amplitude of the surge level fluctuations is 1 - 2 m (Fig.2.22), sometimes reaching 2.5 m [*Mustafin 1961; Soviet Arctic 1970; Dobrovolskiy, Zalogin 1982*]. The amplitude of seasonal level changes as a rule, does not exceed 30-40 cm and actually over the entire sea area the minimum level height is observed in spring and the maximum - in summer (Fig.2.23) [*Dvorkin et al. 1978*]. The climatic level change of the Laptev Sea has everywhere a positive trend (Fig.2.24). Fig.2.25 presents spectral characteristics of the level change for three points of the Laptev Sea. The most significant appear to be the periods of half a year and 11 years. The latter is, obviously, related with an 11

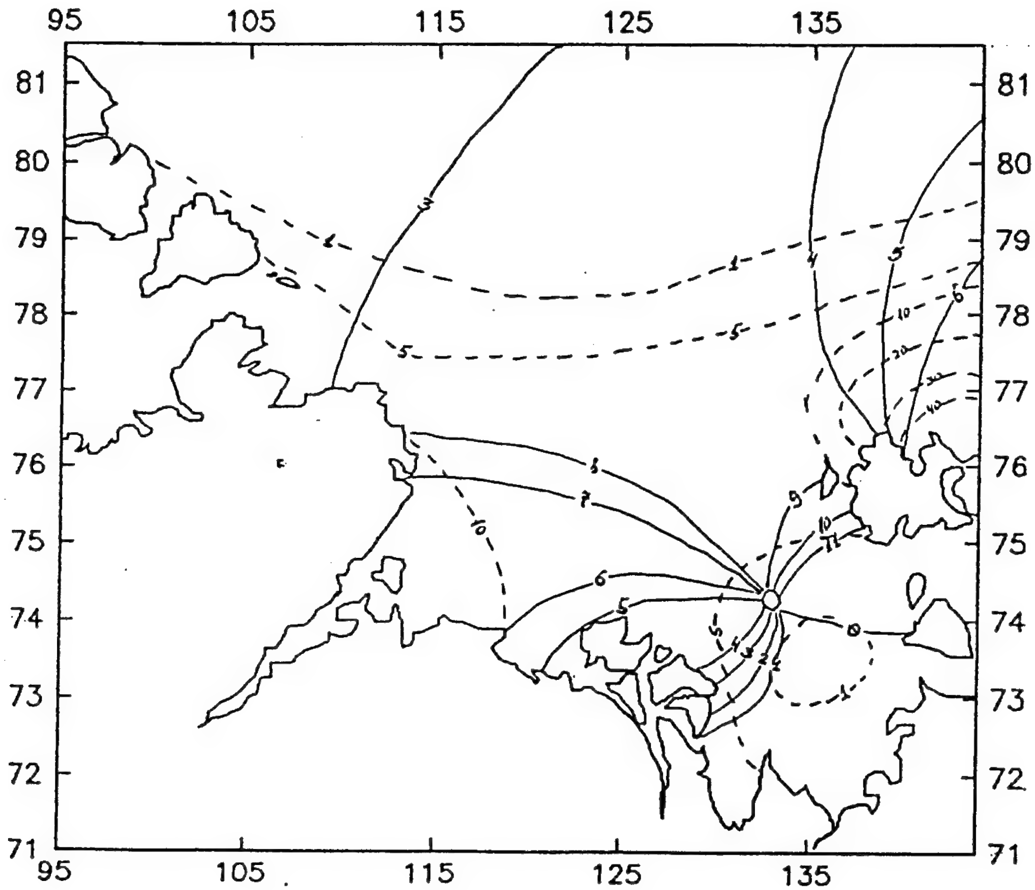


Fig. 2.21. A scheme of the M2 tidal wave propagation
[Proshutinskiy 1993] .

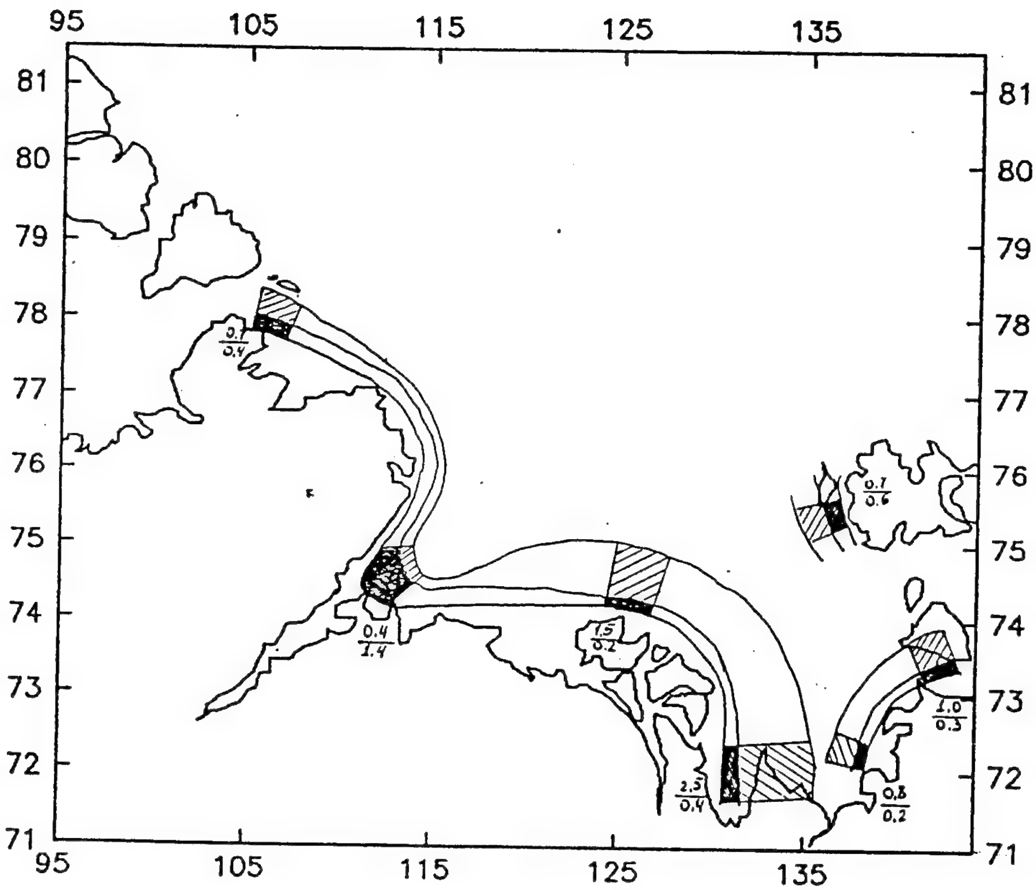


Fig. 2.22. Mean values of the storm surges, m (numerator) and tides, m (denominator).
[Soviet Arctic 1970]

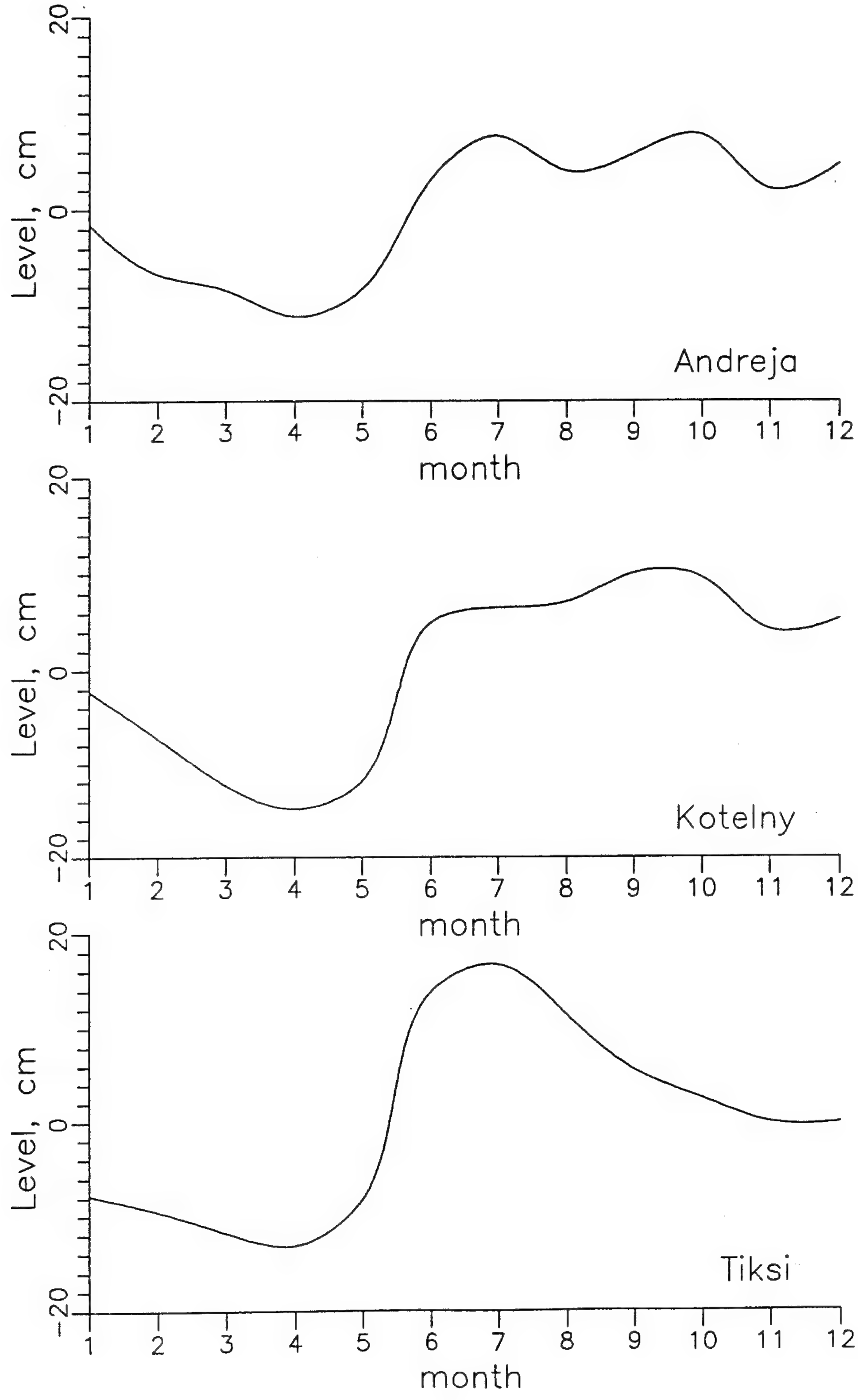


Fig. 2.23. The interannual change of mean multiyear sea level in the deviations from mean annual one according to the observations at the Andrey island, Kotel'ny island, Tiksi Bay

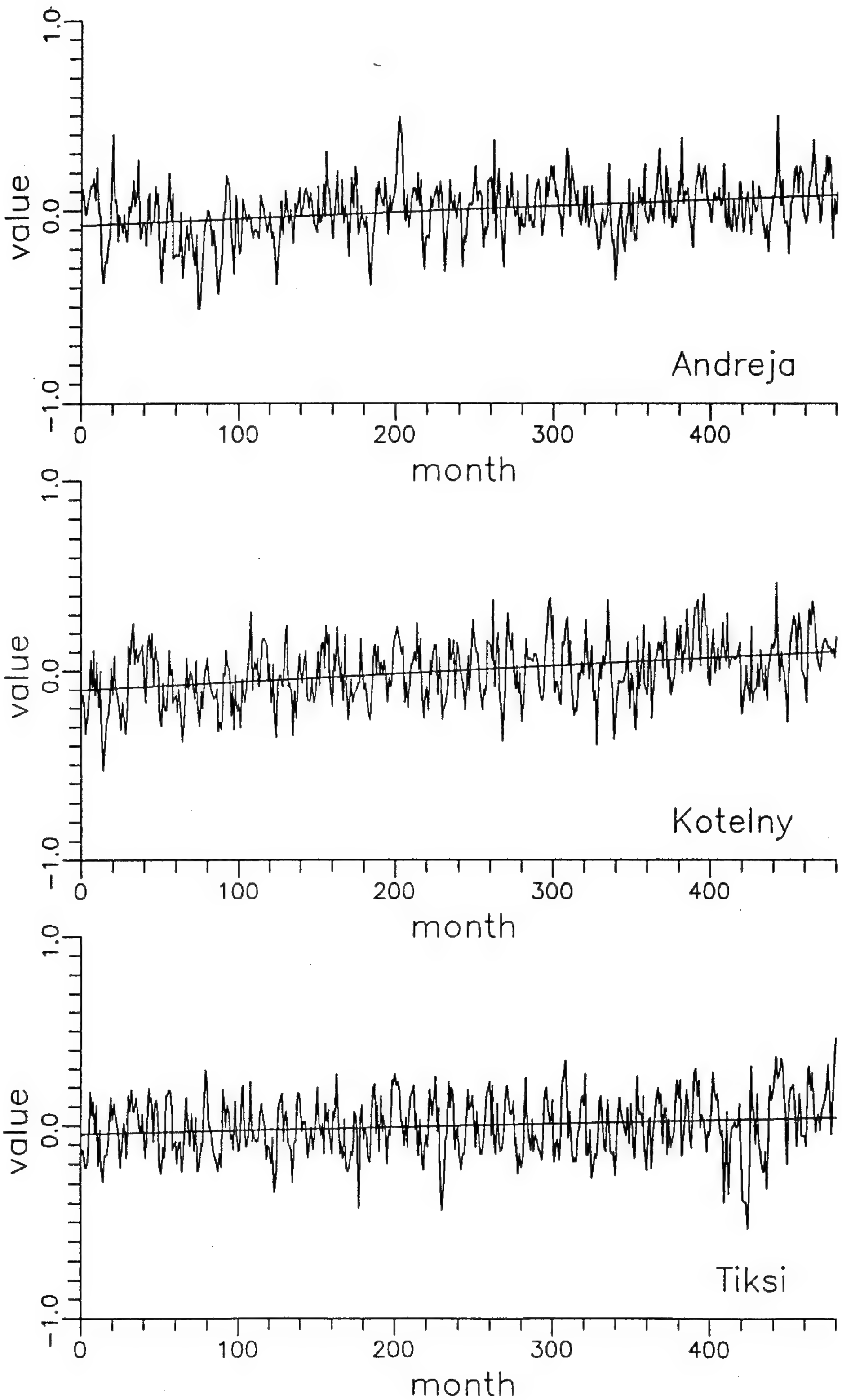


Fig. 2.24. Mean monthly oscillations at the points of the Andrey island, Kotel'ny island, Tiksi Bay from the beginning of the observation period (January, 1953) and a linear climatic trend

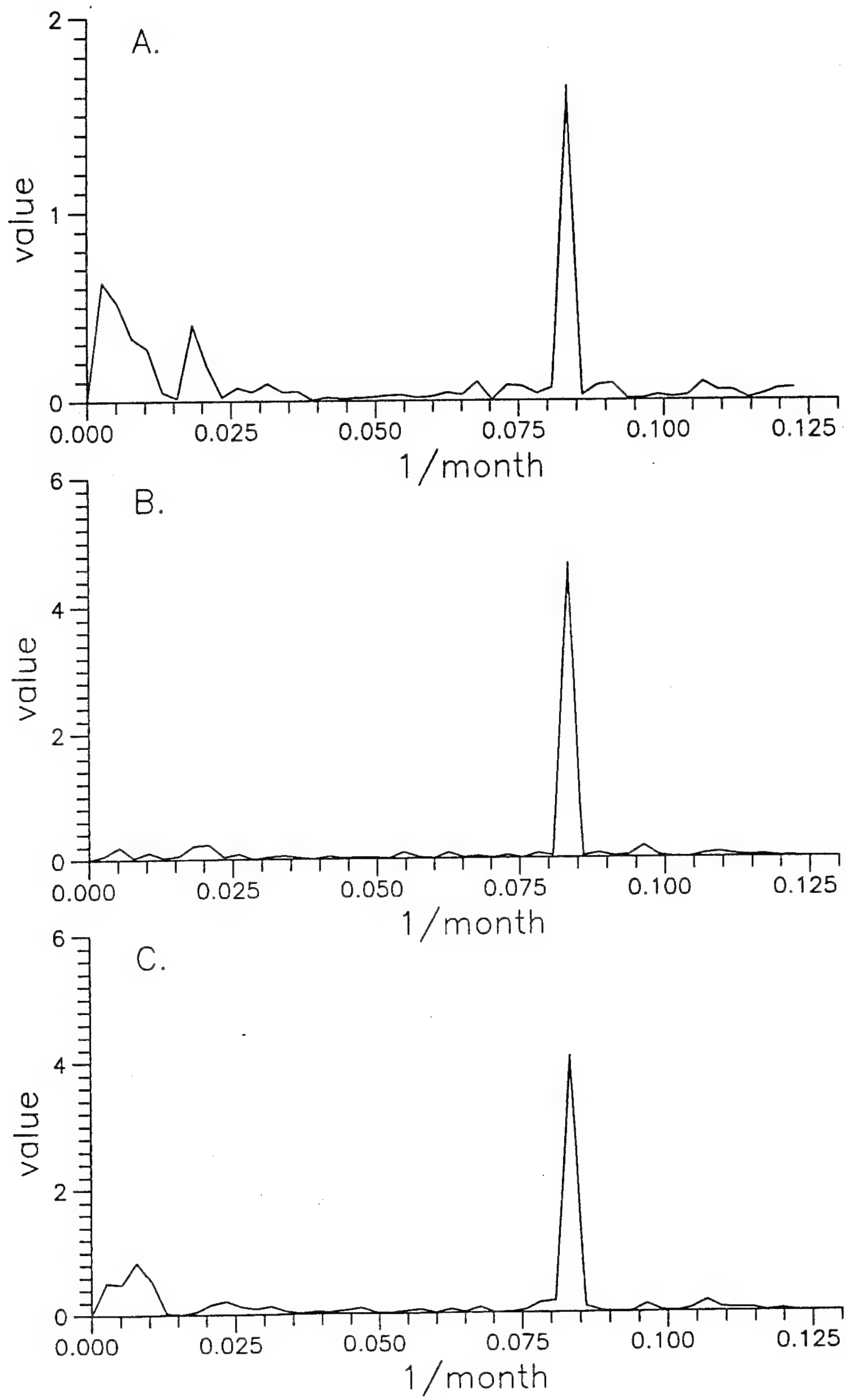


Fig. 2.25. Spectrogram of mean monthly oscillations at the Andrey island (a), Kotel'ny island (b), Tiksi Bay (c).

year period of solar activity variability.

2.11. Ice regime of the Laptev Sea.

The Laptev Sea is covered by ice of different thickness and age category much of the year from October to May (Fig.2.26.b). Ice formation begins in late September. In winter at small depths, less than 20-25 m vast fast ice is formed up to 2 m thick. The fast ice area is equal approximately to 30% of the entire sea area [*Dobrovolskiy, Zalogin 1982; Romanov 1992*]. To the north of the fast ice zone there is drifting ice. Practically every year behind the fast ice zone a significant area of polynyas and young ice is preserved. The width of this zone varies from tens to several hundreds of kilometers. In summer the ice edge often changes its position as affected by wind and currents. The limits of the ice cover extent in summer are given in Fig.2.26.a. The Laptev Sea has an intensive water exchange with the adjacent regions of the Arctic basin, as well as with the Kara and East-Siberian Seas. The estimates of mean annual ice exchange are given in Table 2.8 [*Gorbunov 1979*].

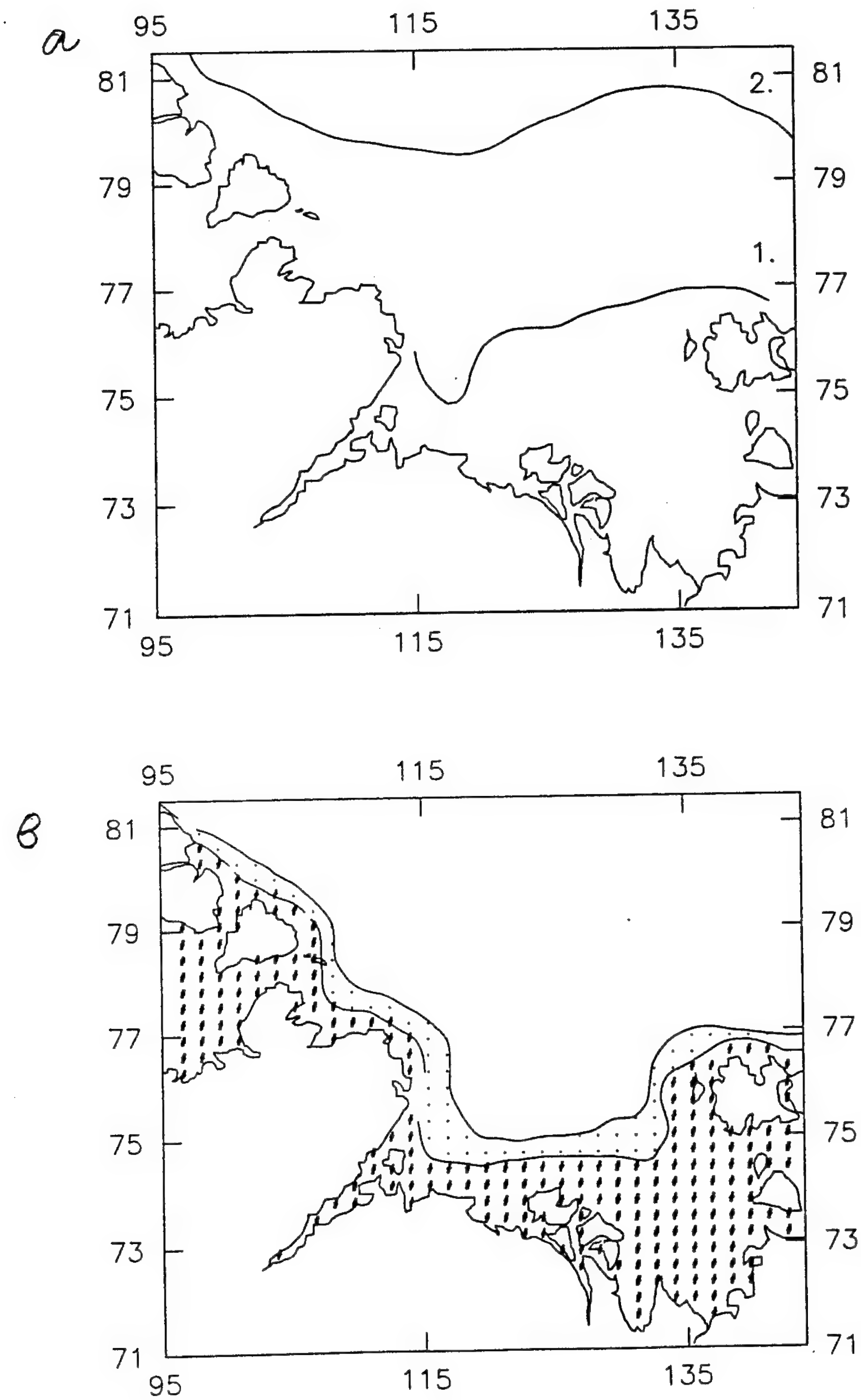


Fig. 2.26. Ice cover of the Laptev Sea
a - mean multiyear (1) and maximum (2) northern position of the drifting ice edge in the summer
b - the ice cover structure of the Laptev Sea in the winter

::: - zone of regular behind-fast polynyas;

- fast ice; - drifting ice.

[Soviet Arctic 1970]

Table 2.8

Ice exchange through the straits of the New-Siberian islands by the data of the "POLEX" experiment, 1976.

Period	Dm. Lapteva		Sannikova		Between Islands Stolbovoy and S. Lyakhovsky	
	S, $км^2$	Q, $км^3$	S, $км^2$	Q, $км^3$	S, $км^2$	Q, $км^3$
13-19 July	-1890	-2.12	fast ice		fast ice	
19-22 July	-1062	-1,05	-350	-0,34	-2087	-2,06
22-25 July	0	0	+800	+0,74	+1525	+1,40
25-28 July	-1467	-1,23	-850	-0,71	+2858	+2,40
28-31 July	-1899	-1,56	-880	-0,72	+3372	+2,76
31 July-3 August	+1089	+0,86	-368	-0.29	+857	+0.68
3-6 August	-1497	-1.14	-331	-0.25	+1730	+1.30
6-9 August	+1420	+1.02	+264	+0.19	+1409	+1.01
9-11 August	+694	+0.49	+123	+0.09	+778	+0.54
11-13 August	0	0	0	0	+104	+0.07
Total	-4612	-4.73	-1592	-1.29	+10546	+8.11

Note: the sign "+" marks the ice drift in straits of Dmitry Laptev and Sannikov to the west, between the islands Stolbovoy and Small Lyakhovsky - to the south.

3. THE EAST-SIBERIAN SEA

3.1. Physical-geographical characteristics

The East-Siberian Sea is partly limited by natural borders and partly - by arbitrary lines. Its western boundary passes from the crossing point of the meridian of the northern tip of the Kotel'ny island with an edge of a continental shoal (79^0 N, 139^0 E) to the northern tip of this island (Anisiy cape), then along its western shore and then follows the eastern boundary of the Laptev Sea. The northern boundary passes by the edge of the continental shoal from the point with coordinates 76^0 N, 180^0 of longitude, and the eastern boundary from the point with these coordinates along meridian 180^0 up to the Wrangel island, then along its north-western shore to the Blossom cape and then farther to the Yakan cape at the mainland. The southern boundary passes along the mainland coast from the Yakan cape to the Svyatoy Nos cape [*Dobrovolskiy, Zalogin 1982; World Ocean Altas, volume 3, Arctic Ocean 1980; Baskakov 1978*].

By its geographical location and hydrological conditions the East-Siberian Sea is assigned to the type of the continental marginal seas.

The largest sea length by parallel 74^0 30' N between the boundary meridians 139^0E and 180^0 is about 640 miles. The largest width in the middle sea area approximately by meridian of the Kolyma river constitutes 506 miles.

The bottom topography of the East-Siberian Sea is very level and it is comparatively shallow as compared with the other marginal seas of the Arctic Basin. The prevailing depths in the western and central regions of the sea are 10-20 m, in the eastern region - 30-40 m [*Soviet Arctic 1970*].

The southern shore of the East-Siberian Sea up to the Kolyma river presents a monotone plain. To the east of the Kolyma river mouth the shore is hillocky, some tops reach a 1000 m height.

Off the western boundary there is a large Archipelago of the New-Siberian islands, which is divided into three main groups of islands: the Lyakhovsky islands (Large and Small Lyakhovsky islands), Anjou islands (Belk'ovsky, Kotel'ny, Bunge land,

Faddeyevsky, Novaya Sibir' islands) and the De-Long islands (Bennet, Zhokhov, Janette, Henriette islands). The relief of the New-Siberian islands is quite diverse: the Lyakhovsky islands, the Kotel'ny and Novaya Sibir' islands are hillocky with some mountains, the Bunge Land island is low land and with the on-shore winds, inducing level rise it is partly submerged under water. The De Long islands are high and rocky.

Off the southern shore of the East-Siberian Sea there are Medvezhiy and Aion islands. Near the eastern boundary there is the Wrangel island, which is separated from the mainland by a deep Long strait [*World ocean Altas, volume 3, Arctic Ocean 1980; Dobrovolskiy, Zalogin 1982*].

3.2. Meteorological regime and climate

The features of the climate of the East-Siberian Sea are mainly governed by its high-latitudinal position between 69^0 and 79^0 N, the influence of the cold Arctic basin on the one hand and a vast Asian continent on the other hand, as well as by the specific character of the atmospheric circulation in this region. The location of the sea north of the Polar Circle governs the presence of polar night, when the solar radiation influx is absent and a continuous cooling of the underlying surface takes place, and polar day, during which there is a constant solar heat income. The duration of polar night is 50-60 days in the southern part of the sea, increasing to 80-100 days in its northern part. Polar day due to refraction is by about 16 days longer than polar night.

3.2.1. Radiation

The East-Siberian Sea is the most sunny of the seas of the Siberian shelf. The duration of sunshine over its area during the year is 1200 hours in total. In annual variations the largest sunshine duration is observed in April (250-300 hours).

The annual influx of total radiation to the sea surface increases from north-west to south-east, being 2850-2950 Mj/sq.m.

Total radiation consists of scatterred radiation and only 1.3 of it incomes directly from the Sun (direct radiation). Due

to a high transparency of the Arctic air here the intensity of direct radiation is very large, being by 10-15% greater than in mid-latitudes [*Chernigovsky, Marshunova 1965*].

In the annual variations the largest solar radiation income falls on May-June (40-50% of the annual sum). However, during this time the sea is still covered with solid ice and snow with a high reflectivity. That is why 60% of incoming radiation outgoes to the atmosphere. On an average during the year, the sum of absorbed radiation by sea surface does not exceed 1000-1500 Mj/sq.m, and in the northern sea - 800 Mj/sq.m. While the largest radiation income is observed in May-June, its maximum absorption falls on July, when the snow cover melts.

The radiation balance of the underlying surface is an indicative characteristics of the radiation regime of the sea. Fig.3.1 presents the distribution of annual variations of the radiation balance in the sea region in calories per sq.cm a year. It is seen, that the radiation balance in the sea is positive. However, much of the year (September-April) the radiation balance is negative. During the summer months (May-August) the radiation balance, especially during the central months, reaches large values, which form positive values for the year.

Fig.3.2 gives maps of the radiation balance distribution in January and July. As is seen, in January the negative radiation balance over the sea is everywhere uniform. In July the radiation balance values increase from north to south. In the southern sea its values are comparable with the radiation balance values in mid-latitudes [*Chernigovsky, Marshunova 1965*].

3.2.2. Underlying surface

The climate of the East-Siberian Sea is to a great extent, governed by the underlying surface. The main effect on climate is produced by sea currents, ice cover extent, orography of the coastal continental zone.

For about 10 months a year the sea is ice-covered and does not become completely ice-free even at the end of the Arctic summer. Only in August the south-western sea is free from the ice cover. The remaining sea area is occupied by drifting ice also in summer. East of the Shelagsky Cape multiyear ice often blocks the

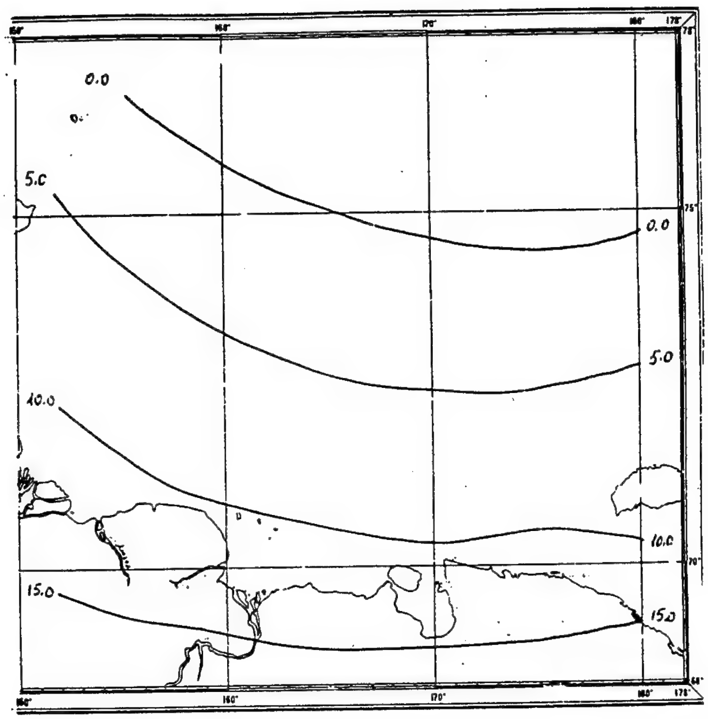


Fig 3.1. Distribution of the annual radiation balance (Kkal/year·cm^2) of the underlying surface in the East-Siberian Sea [Chernigovsky, Marshunova 1965].

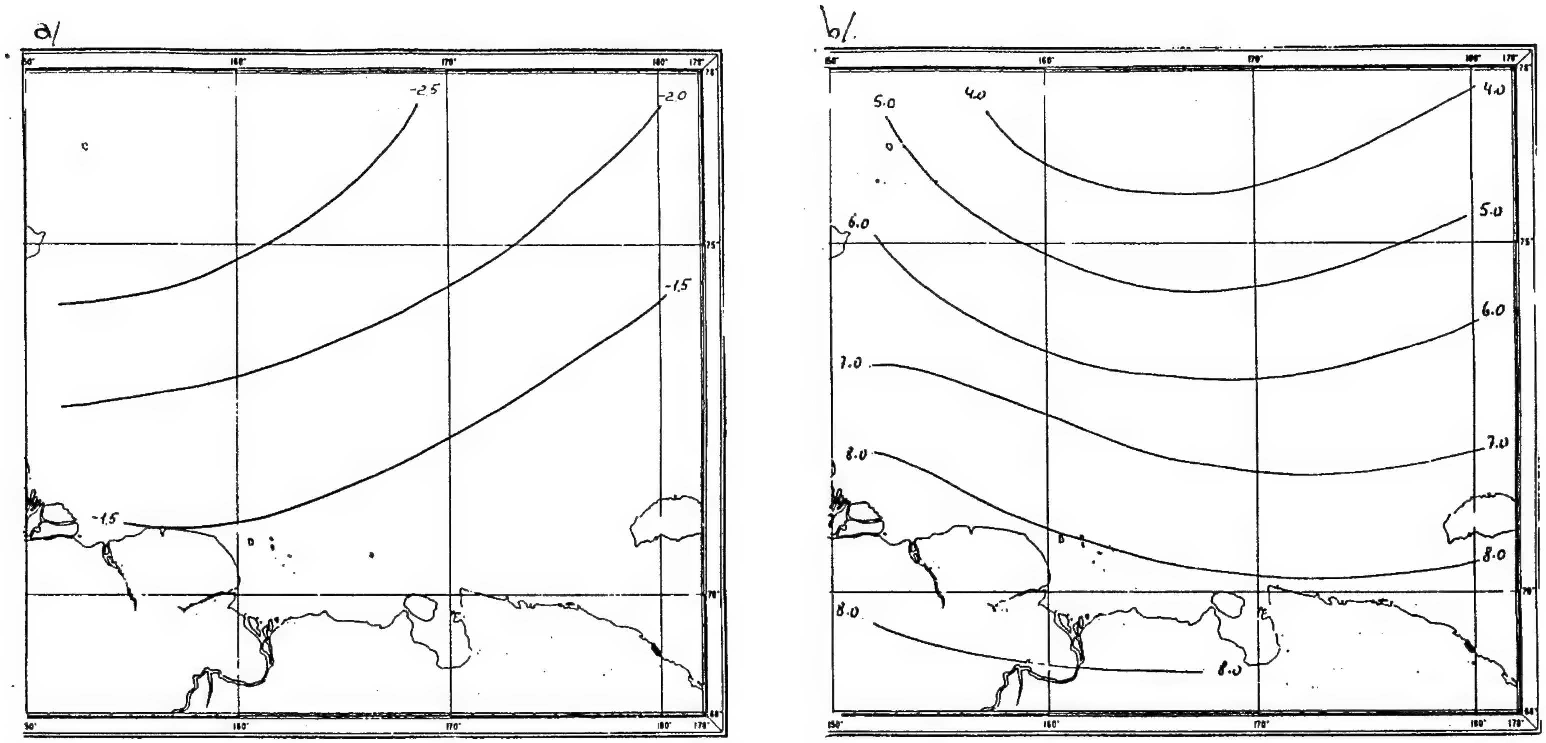


Fig 3.2. Distribution of the radiation balance ($Kkal/month \cdot cm^2$) of the underlying surface in the East-Siberian Sea (a) - for January and (b) - for July. [Chernigovsky, Marshunova 1965].

coastal zone. In October the sea becomes ice-covered.

Ice with snow appears to be a strong reflector, reflecting more than 80% of the incoming solar radiation. It regulates the heat exchange between the ocean and the atmosphere. In winter there is a slow heat release to the atmosphere through ice. As a result, the air temperature over the sea during the winter months is a little higher, than over the continent and the Arctic basin. Specific meteorological conditions form along the ice edge. Here significant contrasts of temperature, humidity and cloud are noted. The largest occurrence frequency of fogs is usually confined to the ice edge.

In coastal regions the orography has a large influence on the climatic features. Mountainous massifs, approaching the sea from the south, prevent the passage of the Pacific cyclones. As affected by elevations, coastline, straits and bays, the air flows can significantly deviate from the direction, prescribed by the pressure relief.

3.2.3. Atmospheric circulation

Transformation of solar energy at the sea surface is considered to be one of the most important factors in the formation of its climate. The atmospheric circulation and associated distribution of pressure fields play a similarly important role [*Soviet Arctic 1970; Prik 1959*].

Fig.3.3 presents distributions of pressure fields, prepared for the winter, spring, summer and fall seasons. During the winter season (November-March) (Fig.3.3.a) the circulation over the sea is governed by the area of decreased pressure over the northern part and a protrusion of high pressure over the southern part. Quite often the exits of deep cyclones to the north-western sea region are observed in winter from the north-west, where they, as a rule, are filled. Most frequent exits of cyclones are observed in February-March. The protrusion of the increased pressure trough of the Siberian High, extending to the southern regions of the sea, creates a small-gradient pressure field over them.

In spring (April-May) the pattern of the atmospheric circulation changes. The Siberian and Canadian Highs disappear,

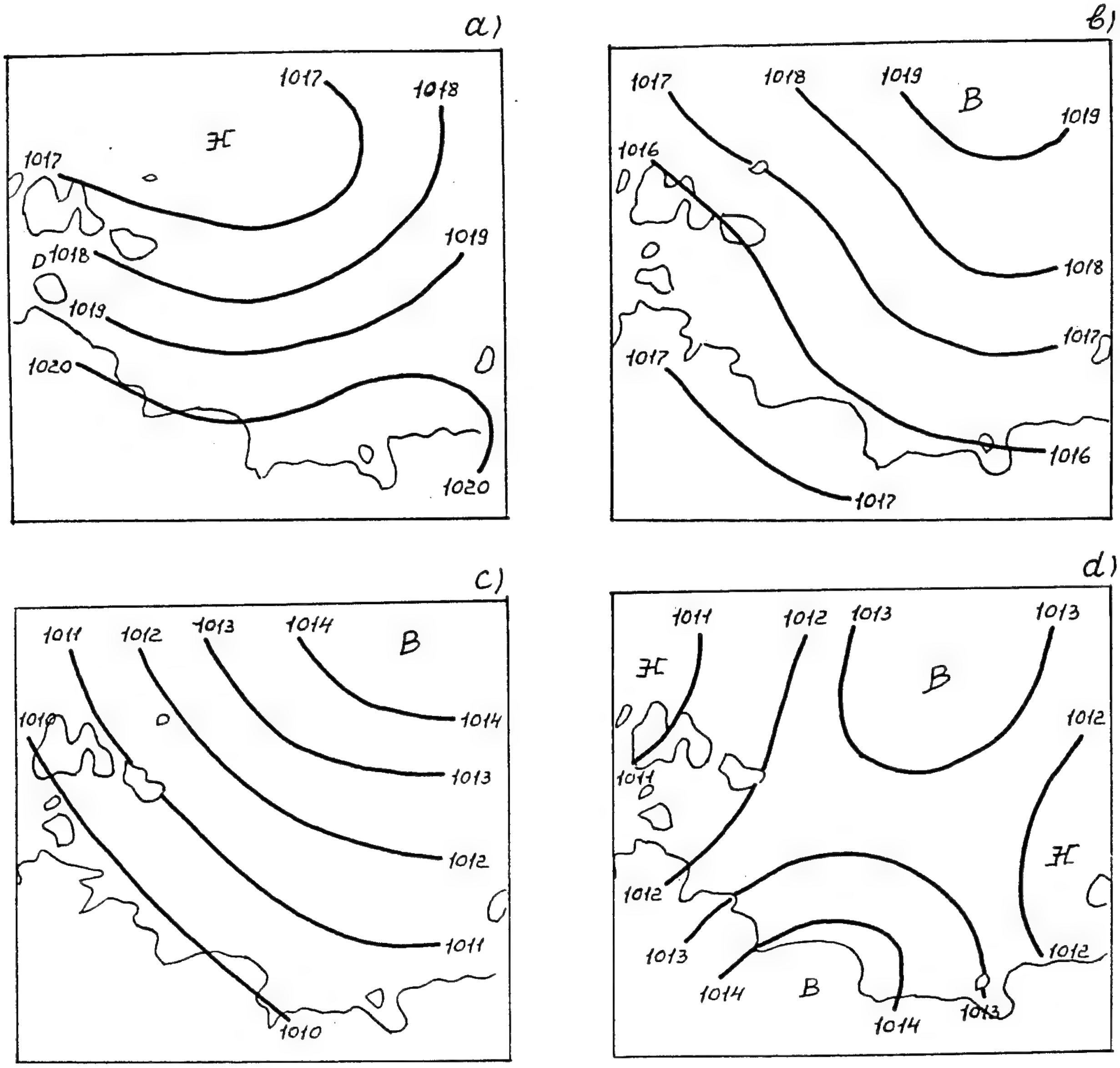


Fig. 3.3. The seasonal distribution of pressure fields
over the East-Siberian Sea
a) in winter, b) in spring,
c) in summer, d) in autumn.
[Soviet Arctic 1970]

the Aleutian depression sharply attenuates. Simultaneously, an area of increased pressure is formed over the Beaufort Sea, the branch of which mainly governs the circulation regime of the sea. Mean seasonal pressure field over the sea is given in Fig.3.3.b. In spring the number of cyclones passing over the sea decreases to a minimum, being 1-2 cyclones a month.

In summer the circulation over the sea is governed by the southern periphery of the Arctic anticyclone and the northern periphery of the decreased pressure depression, located over Siberia (Fig.3.3.c). Frequently the exits of low cyclones to the sea are observed from the side of the Siberian depression. Their number in June-July increases to 4-5 a month.

In the fall (September-October) the pattern of the pressure field changes with a specific distribution structure of cyclones and anticyclones over the sea (Fig.3.3.d). The southern and northern sea regions are under the effect of increased pressure areas. The areas of decreased pressure are located over the western and eastern regions.

3.2.4. Wind regime

The presented distributions of pressure fields during the seasons form respective directions of prevailing air transports over the sea. Fig.3.4 presents multiyear occurrence frequency of the directions of air transports over the sea in the indicated seasons.

During the winter season in accordance with the circulation conditions (Fig.3.4.a) the air transports of south-western (35%) and north-eastern directions (20%) prevail. The occurrence frequency of air transports of other directions is much lower. Mean wind speeds in winter are 5-6 m/s.

In spring in connection with the change of the circulation pattern the eastern (40%) and north-eastern (20%) transports of air masses become predominant (Fig.3.4.a). Mean wind speed over the sea is within 5-6 m/s.

In the summer and fall periods (Fig.3.4.b) an increased frequency of the directions of air mass transport falls on the eastern and north-eastern directions. And the frequency of the eastern directions in summer (40%) is higher, than in the fall

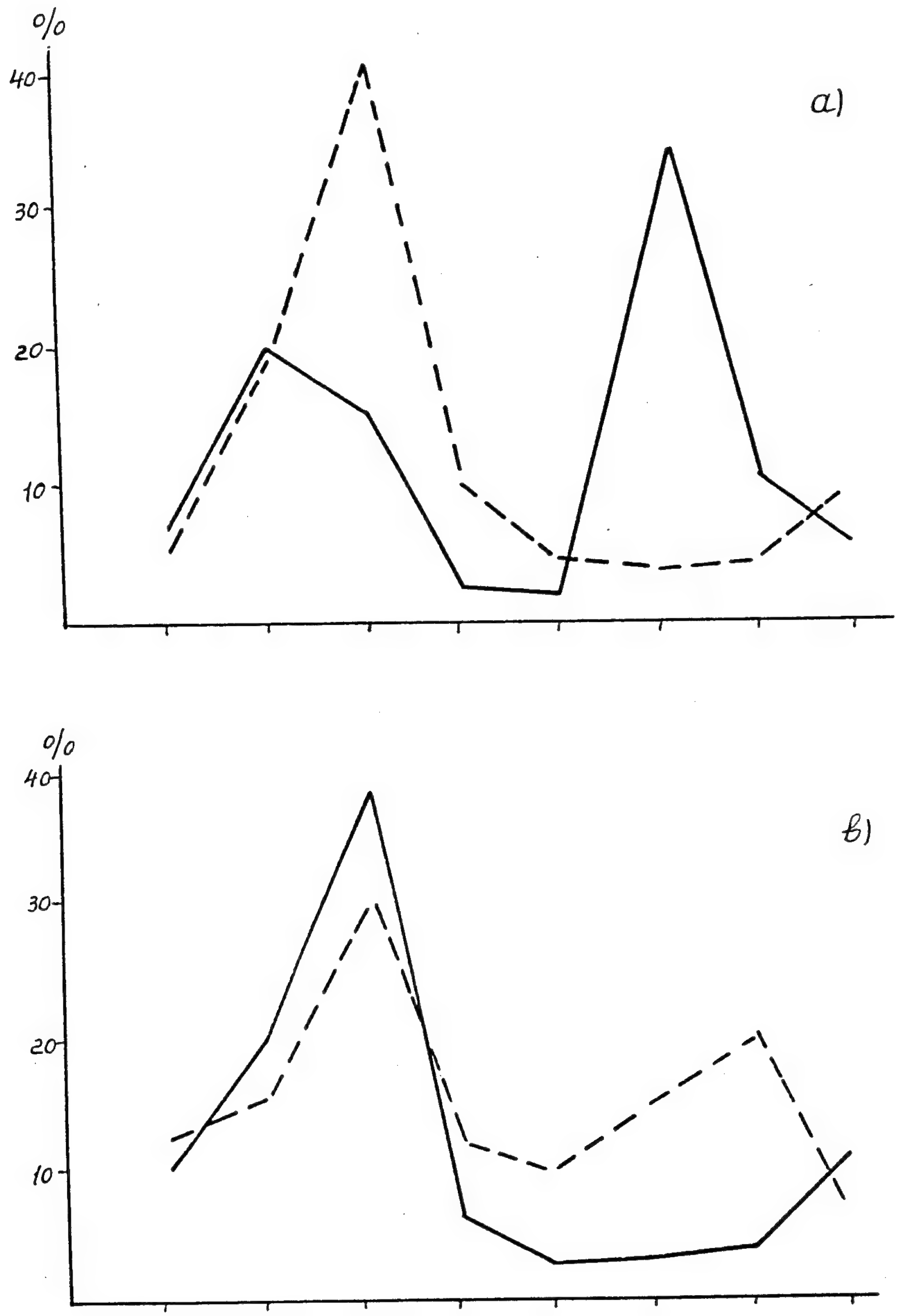


Fig. 3.4. Multiyear occurrence frequency of the directions of air flows over the East-Siberian Sea
a) ——— winter, ----- spring,
b) ——— summer, ----- autumn.
[Atlas of the oceans. The Arctic Ocean. 1980]

(30%). But in the fall an increased frequency of the western (20%) and south-western (15%) directions is recorded.

Regular observations of the storm winds are carried out only at the coastal stations. The number of the days with storms (more than 15 m/s) at the coast of the East-Siberian Sea) changes within a significant range (from 83 to 111 cases a year). In the west they are more frequent than in the east of the coast. The absence of well-pronounced annual variations in the frequency of strong winds, which can be observed during all months of the year without exception is typical. In some years the number of days with a storm wind can be 1.5-2 times more or less than mean multiyear values. Most storm winds are the winds of the western direction. In the spring-summer time the east and north-east winds often reach a storm force. Table.3.1 presents mean and maximum number of days with a strong wind.

Table 3.1

Mean and maximum number of days with strong wind (more than 15 m/s)

Regions	Months												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Western	5	2	2	2	2	2	1	1	3	2	3	2	27
East-Siberian Sea	11	9	6	7	6	5	4	4	12	6	7	6	83
Eastern	6	6	5	7	5	6	8	4	5	5	6	7	70
East-Siberian Sea	10	13	8	11	7	9	11	7	7	8	9	11	111

Note: mean - in the numerator, maximum days with strong wind - in the denominator.

Of local storm winds a particular attention should be paid to "juzhak" in the Pevek inlet - a strong south-east wind with gusts, which is accompanied by a foehn phenomenon [*Soviet Arctic*

1970; Climate features 1985]. This wind appears suddenly, its speed reaching the tornado force up to 40-50 m/s. The zone of the effect of this wind does not exceed several kilometers by width. In the sea its effect extends over tens of kilometers. The storm winds of a foehn character are also observed in the Ambarchik inlet and at Shelagsky cape.

3.2.5. Temperature

The thermal regime over the East-Siberian Sea is governed by a spatial air temperature distribution, changing significantly from season to season [*Soviet Arctic 1970*].

Mean monthly temperature in the winter season changes from -26^0 C in the east to -30^0 C in the west, near the New-Siberian islands. In spring (April-May) a small gradient temperature field is formed. Mean temperature in April changes from -18^0 C in the eastern sea to -20-21^0 C in the north-western sea.

In summer the solar radiation influx in the conditions of polar day becomes the main climate-forming factor. There is a stable temperature of about 0^0 C in July-August over the northern sea part. Off the coast it is equal to 4-5^0 C. With the fall (October) the thermal contrasts over the sea attenuate and already in November the winter type of temperature distribution is formed.

The largest intermonthly temperature variability is typical of the transient seasons. From April to May mean air temperature increases by 10-12^0 , and from May to June - by 8-10^0 C. The temperature drop in the fall from September to November occurs with the same rate, but more slowly due to the thermal inertia of the sea.

An absolute amplitude of air temperature variations over the sea area is very large. The difference between absolute annual maxima and minima is equal to 70-80^0 over the open sea and 80-90^0 C in the coastal region.

Negative air temperatures are observed over the sea much of the year. The duration of the period with positive mean daily temperatures is less than two months in the northern part of the sea and 3-3.5 months - in the southern part. A stable temperature transition across 0^0 to positive values occurs in the southern

sea on an average, on 10 June, and in the central sea - on 30 June. The temperature transition across 0^0 in the fall in the north-eastern sea region occurs in late July, and by 15 September the whole sea is in the domain of stable negative air temperatures. The variability of the dates of the temperature transition across 0^0 in the fall is significant. The most early and late dates can differ by 1.5-2 months. The cause of such variation of the dates is attributed to the features of the circulation and ice conditions of some years.

The air temperature over the sea is closely connected with the wind regime. In winter in coastal regions the winds, blowing from the cooled continent, are, as a rule, several degrees colder than the winds, blowing from the sea side. The wind increase, both in winter and in summer usually results in the air temperature increase. Strong frosts are observed at quiet weather. Table 3.2 presents mean monthly temperatures, absolute maxima and minima for the regions of the East-Siberian Sea.

3.2.6. Humidity, cloud, precipitation

Cloud cover, air humidity and precipitation are the main characteristics of the moistening regime. The cloud cover over the sea is characterized by well-pronounced annual variations with a maximum cloud cover in August-September and a minimum in February-March. The occurrence frequency of overcast weather is 80-90% in July-August and 40-50% in January-February.

A relative air humidity over the sea is large throughout the year. The largest values of relative humidity are recorded in July-August: 85-90% in the southern sea region and 92-95% - in the northern region. A high occurrence frequency of precipitation is related, to a considerable extent, with a high relative humidity. In total during the year about 120-150 days with precipitation are observed over the sea. In summer and in the fall the number of days with precipitation is by 1.5 times more than in winter. The least number of days with precipitation is observed in May [*Soviet Arctic 1970*].

In spite of a very large occurrence frequency of precipitation its total sum is insignificant: from 180-200 mm on an average during the year in the northern part of the sea to

Table 3.2

Mean monthly (1), Absolute minimum (2), absolute maximum (3) of air temperature (°C)

Regions	N	Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Western	1	-30.0	-28.0	-20.2	-20.0	-8.7	0.1	2.5	2.5	-0.1	-9.4	-22.0	-27.5	-14.4
	2	-49	-51	-47	-44	-29	-16	-4	-6	-18	-32	-41	-44	-51
East-Siberian Sea	3	-5	-7	-9	1	10	23	22	22	12	7	-3	-4	23
Eastern	1	-24.3	-26.2	-25.6	-18.0	-7.4	1.4	3.0	2.6	-0.5	-9.1	-18.5	-24.6	-12.7
	2	-49	-49	-46	-41	-33	-11	-5	-7	-17	-33	-40	-46	-49
East-Siberian Sea	3	9	4	6	6	14	26	28	25	16	12	6	7	28

250-280 mm in the coastal zone. Half of the annual sum of precipitation falls out in July-September.

3.2.7. Dangerous phenomena

Dangerous weather phenomena include fogs, drifting snow, poor visibility.

Fogs are considered to be a typical feature of the climate of the East-Siberian Sea. In the southern part of the sea on an average over the year there are 50-70 days with fogs. In the north of the sea the number of the days with fogs increases to 90-100 days. More seldom the fogs are observed in winter, 1-2 days with fogs over the month. In spring the number of days with fog increases to 6-10, and in June-August, on an average, every second day is accompanied by fog formation.

The fog occurrence frequency depends, to a greater extent, on the character of the underlying surface. With the increase of ice concentration, the probability of the fog appearance increases but at ice concentration being 10/10, it decreases.

The fogs in the summertime are usually related with the advection of warm and moist air to the cold underlying surface. They cover considerable areas, differing by large vertical thickness and a sudden occurrence. Table 3.3 shows mean and maximum number of days with fog in the regions of the East-Siberian Sea [*Soviet Arctic 1970*].

During the colder part of the year from October to May the East-Siberian Sea is characterized by a high frequency of drifting snow. On an average over the year there are 60-80 days with drifting snow. The duration of drifting snow varies within a significant range - from 10 hours to 200-300 hours. It is more frequent in the eastern part than in the western one. Drifting snow can occur in winter at different temperatures. But it is most frequent at an air temperature below -20-25^0 C. This makes the drifting snow particularly dangerous.

Fogs and drifting snow dramatically reduce the horizontal visibility. The frequency of poor visibility (less than 1 km) has two maxima in the annual variations, in summer and in winter, connected with fogs and drifting snow. In July-August the frequency of poor visibility in the open sea is 20-30%. During

the winter months it does not exceed 10-15%. This is attributed to the fact that at drifting snow the visibility range is not always reduced to 1 km.

Table 3.3

Mean and maximum number of days with fogs

Regions	Months												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Western East-Siberian Sea	1/5	1/8	2/10	3/8	7/15	14/22	16/24	14/26	6/14	3/11	2/6	1/8	70/163
Eastern East-Siberian Sea	2/6	2/6	2/7	3/10	9/21	14/24	19/27	16/27	9/16	3/9	2/8	1/7	82/168

Note: mean - in the numerator, maximum days with fogs - in the denominator.

3.3. Continental run-off

In this section there were used monographs [*Domanitsky et al. 1971; Soviet Arctic 1970*] and handbooks: the State water cadastre. Annual data on the regime and resources of the surface land waters and Resources of surface waters of the USSR, Main hydrological characteristics.

The continental run-off to the East-Siberian Sea is not so large as compared with the Kara and Laptev Seas. The run-off volume to the sea is about 213 cu.km [*Ivanov 1976*].

Fig. 3.5 presents distribution of mean multiyear volume of the run-off of the three main rivers and the contribution of each of them to the total run-off is well evident.

1. The Indigirka river is 1726 km long. The area of the

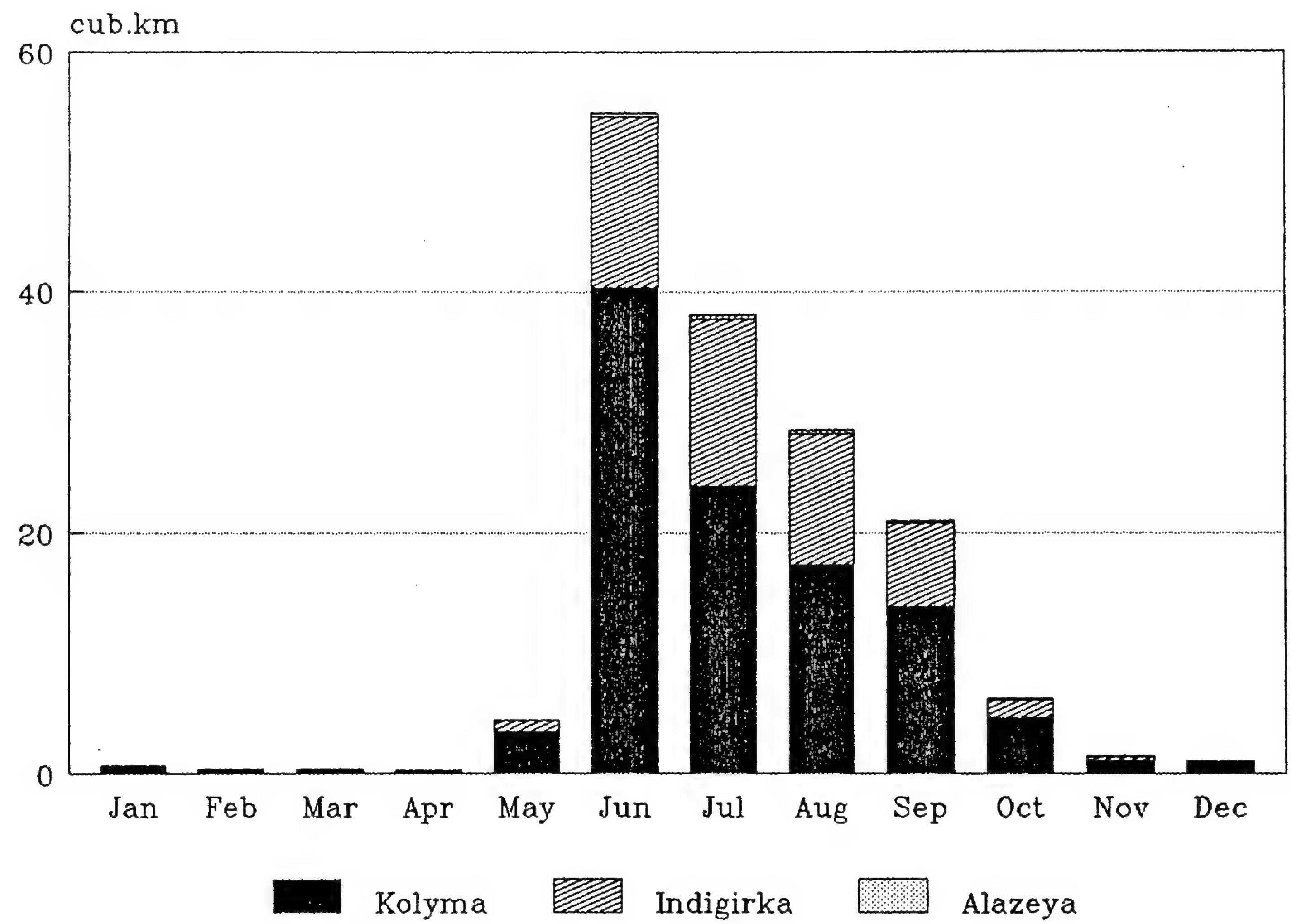


Fig. 3.5. Distribution of mean multiyear volume of the river run-off to the East-Siberian Sea.

water catchment basin is 360 000 sq. km. The river is located in the area of the development of multiyear frozen mountainous rock, which leads to the formation of the ice mounds. When falling into the sea it forms a delta with an area of 5500 sq. km. The Indigirka mouth is separated from the sea by a shallow bar. The river alimentation is by rain and melt water (snow, glacier and water frozen on the ice).

The Indigirka freezes in October and breaks up in late May - early June. In winter the river freezes in some places down to the bottom.

Water discharges are measureed at the gauging section of the river (p.Vorontsovo) from 1937. Mean water discharge is 1565 cu.m/s, maximum - up to 11500 cu.m/s. The diagram of mean multiyear discharges is given in Fig. 3.6. Fig.3.7 presents a percentage ratio of mean monthly water discharges. About 95% of the Indigirka run-off is in June-September. The wave height is up to 11.5 m during the spring flood. Mean annual run-off is about 58 cu.km, solid run-off is about 13.7 mln.t.

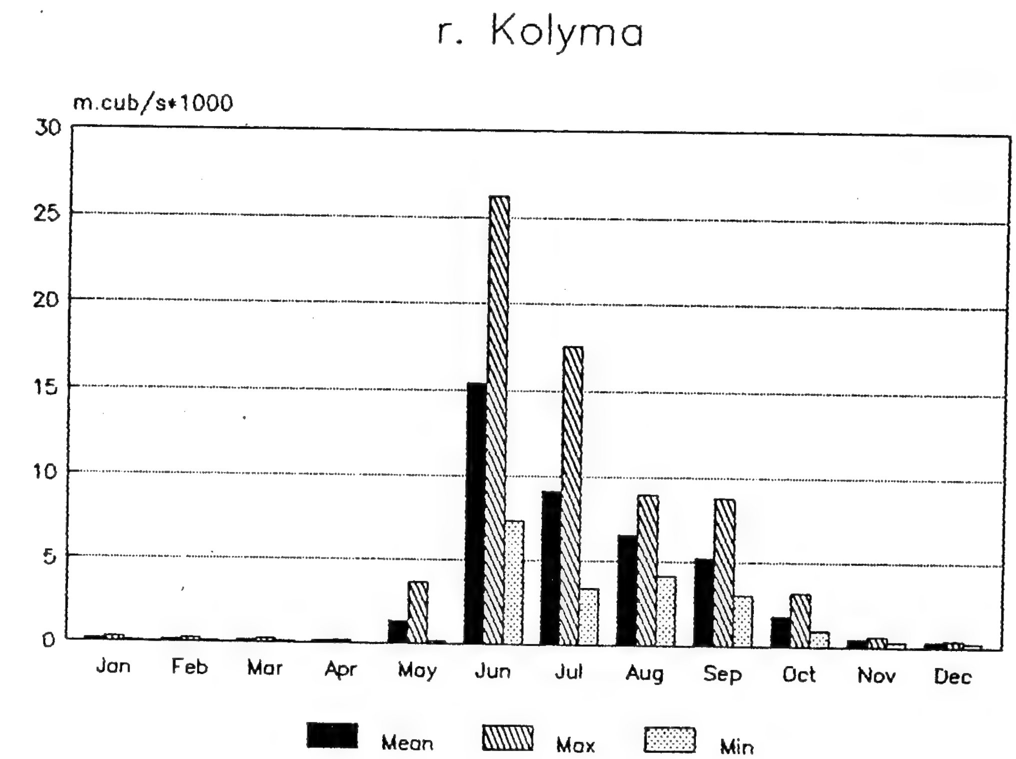
Fig. 3.8 presents the diagram of the variability of mean annual and mean monthly (June) discharges of the Indigirka river. There is some periodicity with periods of about 9 and 4 years, the trend is practically absent.

2. The Kolyma river is 2129 km long with an area of the water catchment basin of 643 000 sq. km. When falling into the sea it forms a delta 110 km long with an area of 3 000 sq. km. The river alimentation is mixed : snow (47%), rain (41%) and underground water (11%).

The spring flood is from mid-May to September. Almost 90% of the river run-off is transported during this period (Fig.3.7). The wave height during the spring flood is up to 14 m.

Water discharge is measured at the gauging section (p.Kolymskoye) from 1977. Mean water discharge is 3400 cu. m/s, maximum - up to 26200 cu.m/s. The diagram of mean multiyear discharges is given in Fig.3.6. Mean annual discharge is about 123 cu.km. Mean sediment run-off is about 5.5 mln. t.

The Kolyma freezes in mid-October. Before freezing such phenomena as ice drift, shuga drift and ice jams are observed. In winter ice mounds are frequent. The river breaks up in the second



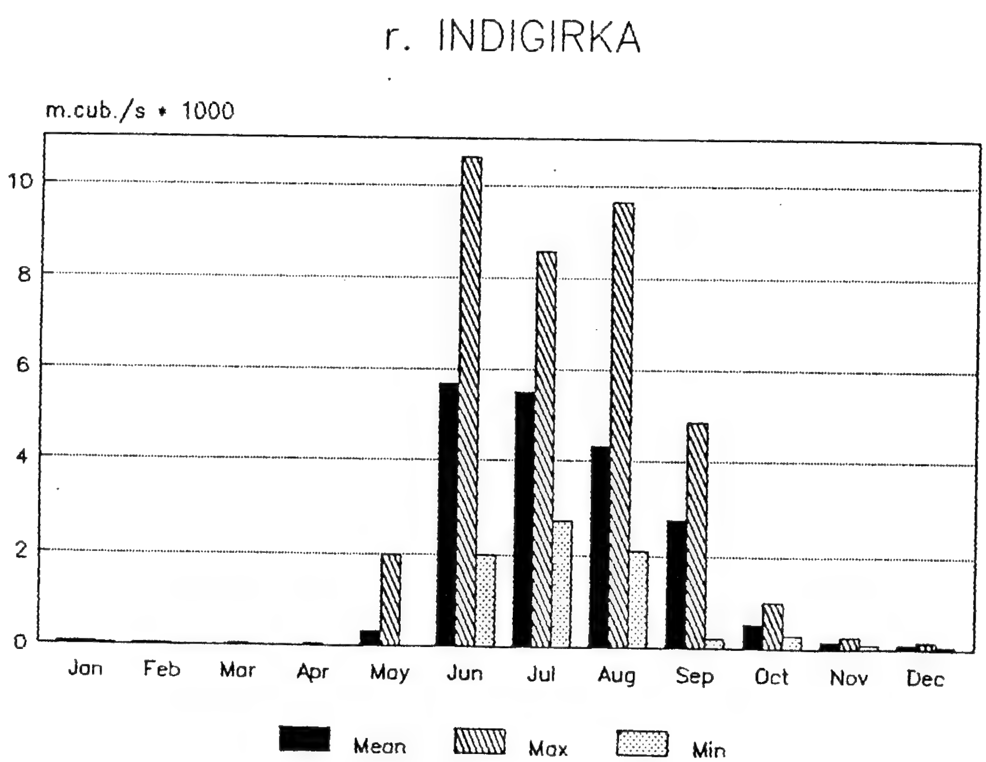


Fig. 3.6. Diagram of mean multiyear water discharges of the rivers Kolyma and Indigirka.

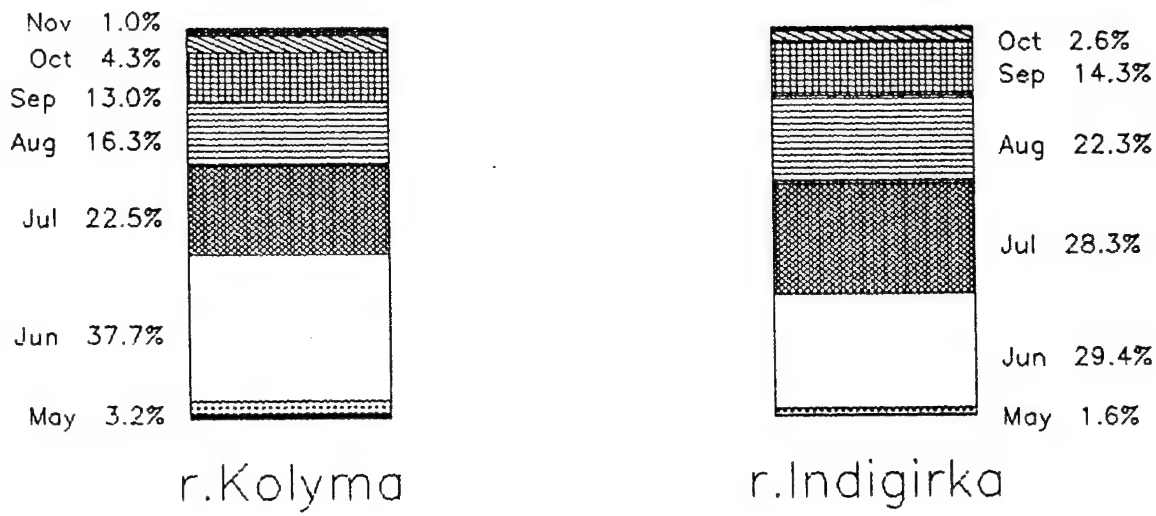


Fig. 3.7. A percentage distribution of the mean multiyear water discharge of the rivers Kolyma and Indigirka.

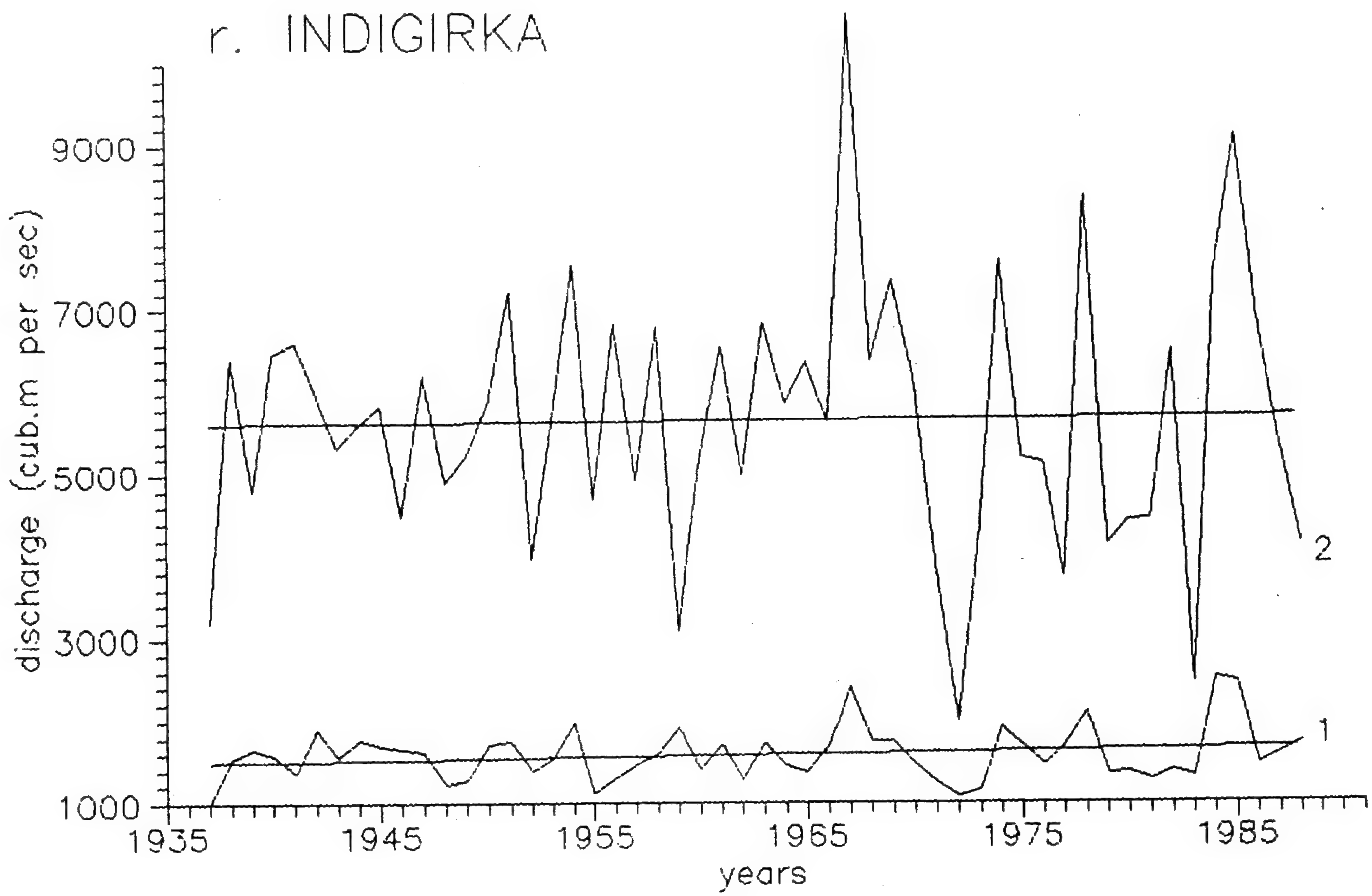


Fig. 3.8. Diagram of the variability of mean annual (1) and mean monthly June (2) discharges of Indigirka.

half of May - early June.

3. The Alazeya river is 1592 km long with an area of the water catchment basin of 64700 sq. km. It is divided in the mouth into some streams. There are more than 24000 lakes at the basin territory. The river alimentation is by snow and rain. The river freezes in late September - early October. It breaks up in late May-early June. Usually the river in winter freezes down to the bottom from mid-December to mid-May.

The water discharge is measured at the gauging section of the river (Andryushkino st.) from 1978. Mean water transport is 43.6 cu.m/s, maximum - up to 320 cu.m/s. Mean annual run-off is about 1.5 cu.km.

3.4. Water masses and thermohaline structure

A high-latitudinal position, an open boundary with the central Arctic basin, large ice cover extent and small river run-off govern the structure and a spatial-temporal variability of oceanographic characteristics of the East-Siberian Sea. The water temperature at the surface in the wintertime decreases from south-west to north-east and is actually everywhere close to the freezing temperatures (Fig.3.9.a). The salinity in winter also has a tendency to increase from south-west to north-east from 17-18 $^0/_{00}$ in the western sea to 32-33 $^0/_{00}$ in the north-eastern sea (Fig.3.9.b). In the summertime the water temperature at the surface decreases from south to north from 5-7^0 C in the coastal zone up to -1 -1.5^0 C in the northern part of the sea (Fig.3.10.a). The salinity increases from south to north from the values 8-10 $^0/_{00}$ in the coastal zone up to 30-32 $^0/_{00}$ near the northern sea boundary (Fig.3.10.b). A vertical water structure in winter is characterized by an insignificamt salinity increase from the surface to the bottom, the temperature changes little and is practically everywhere equal to the freezing temperature (Fig.3.11). In the summertime a typical feature of temperature and salinity is the presence of the zone of large gradients in the 12-15 m layer (Fig.3.12).

Table 3.4 [*Nikiforov, Shpaikher 1980*] presents thermohaline characteristics of the main water masses of the

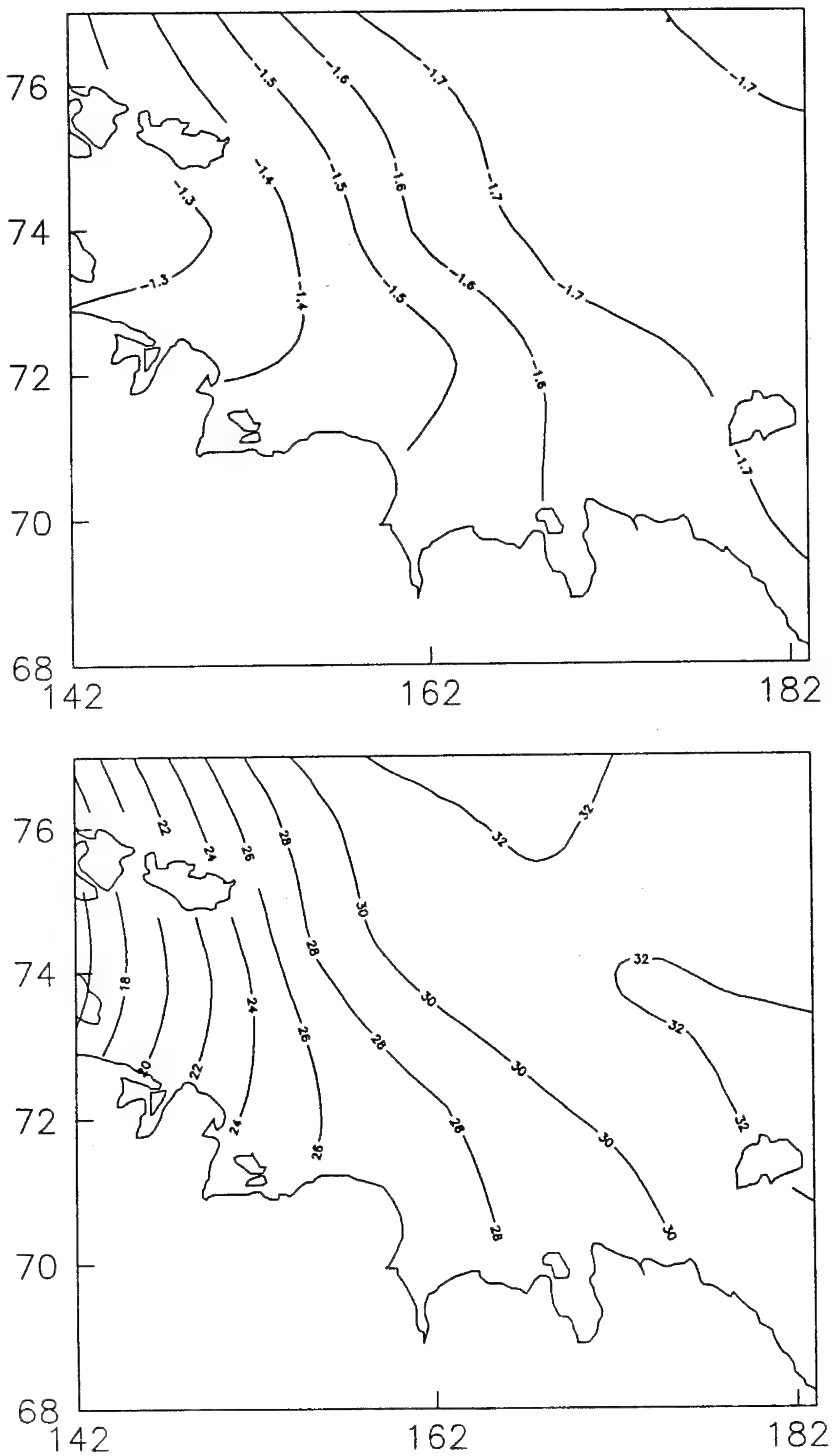


Fig. 3.9. Tipical distributions of the water temperature (a) and salinity (b) at the surface of the East-Siberian Sea in winter

[Dobrovol'skiy, Zalogin 1982]

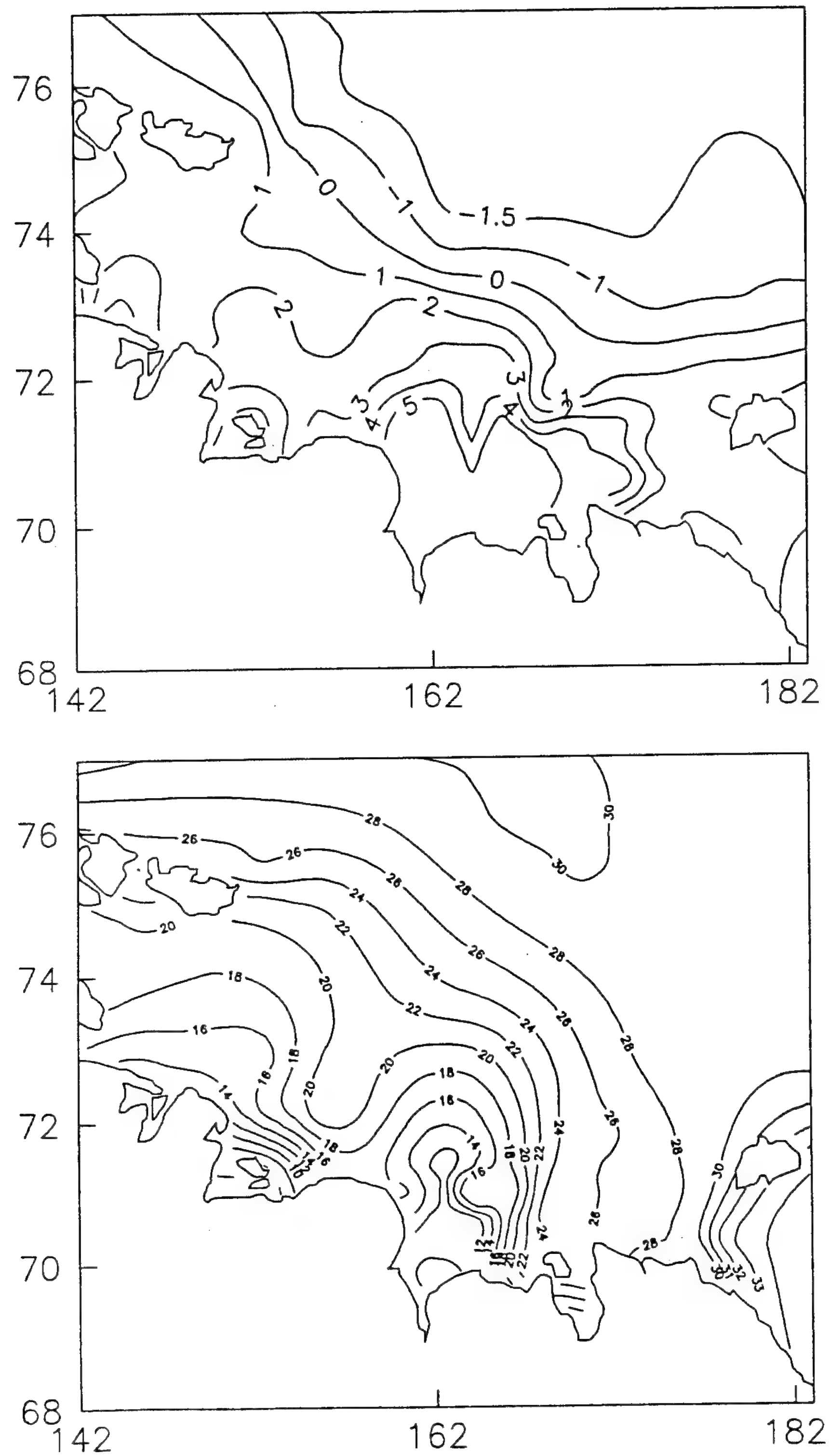


Fig. 3.10. Tipical distributions of the water temperature (a) and salinity (b) at the surface of the East-Siberian Sea in summer

[Dobrovol'skiy, Zalogin 1982]

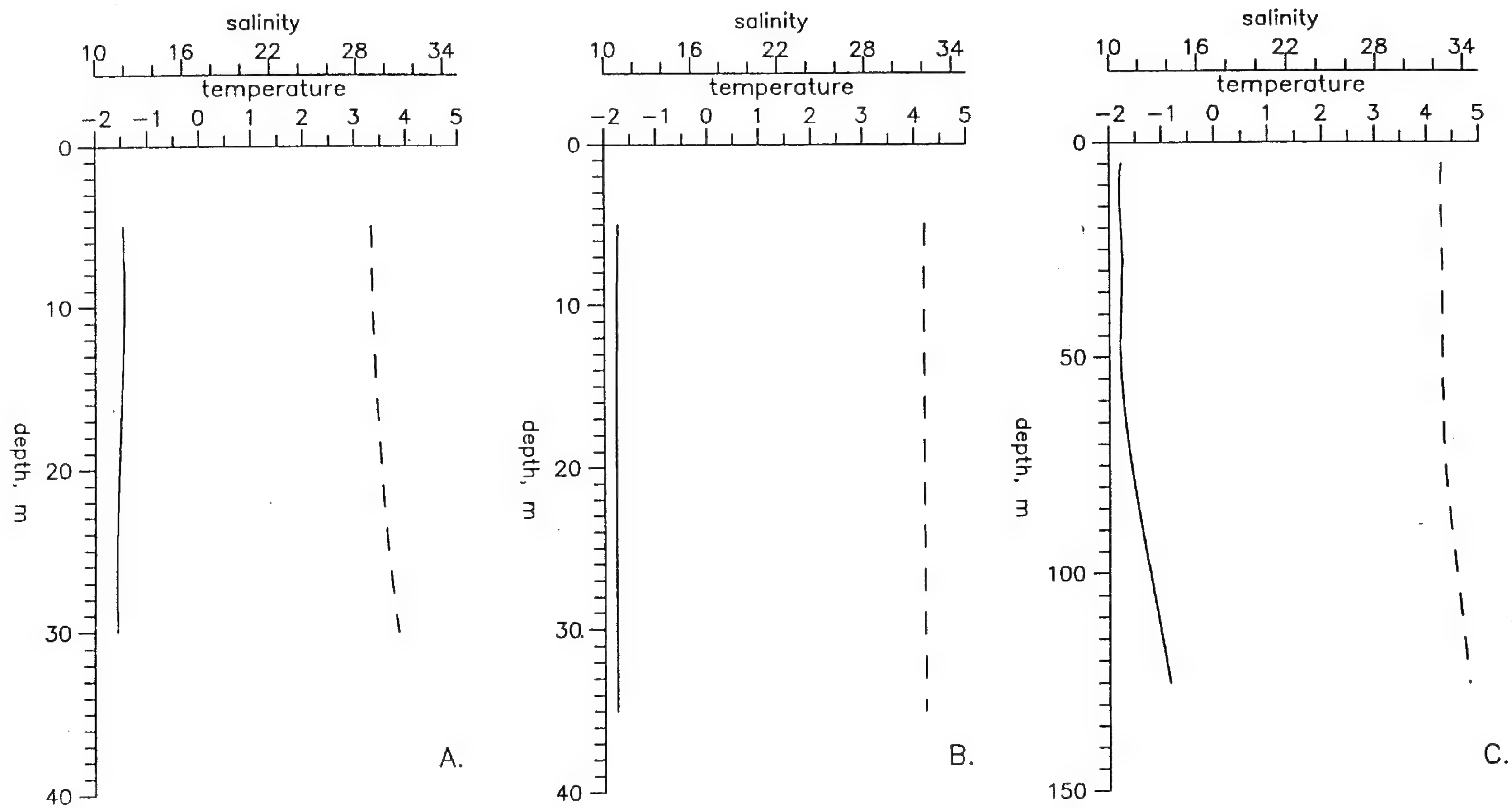


Fig. 3.11. Vertical water temperature and salinity profiles in winter in different parts of the Laptev Sea.
a - south-western, b - south-eastern, c - northern part

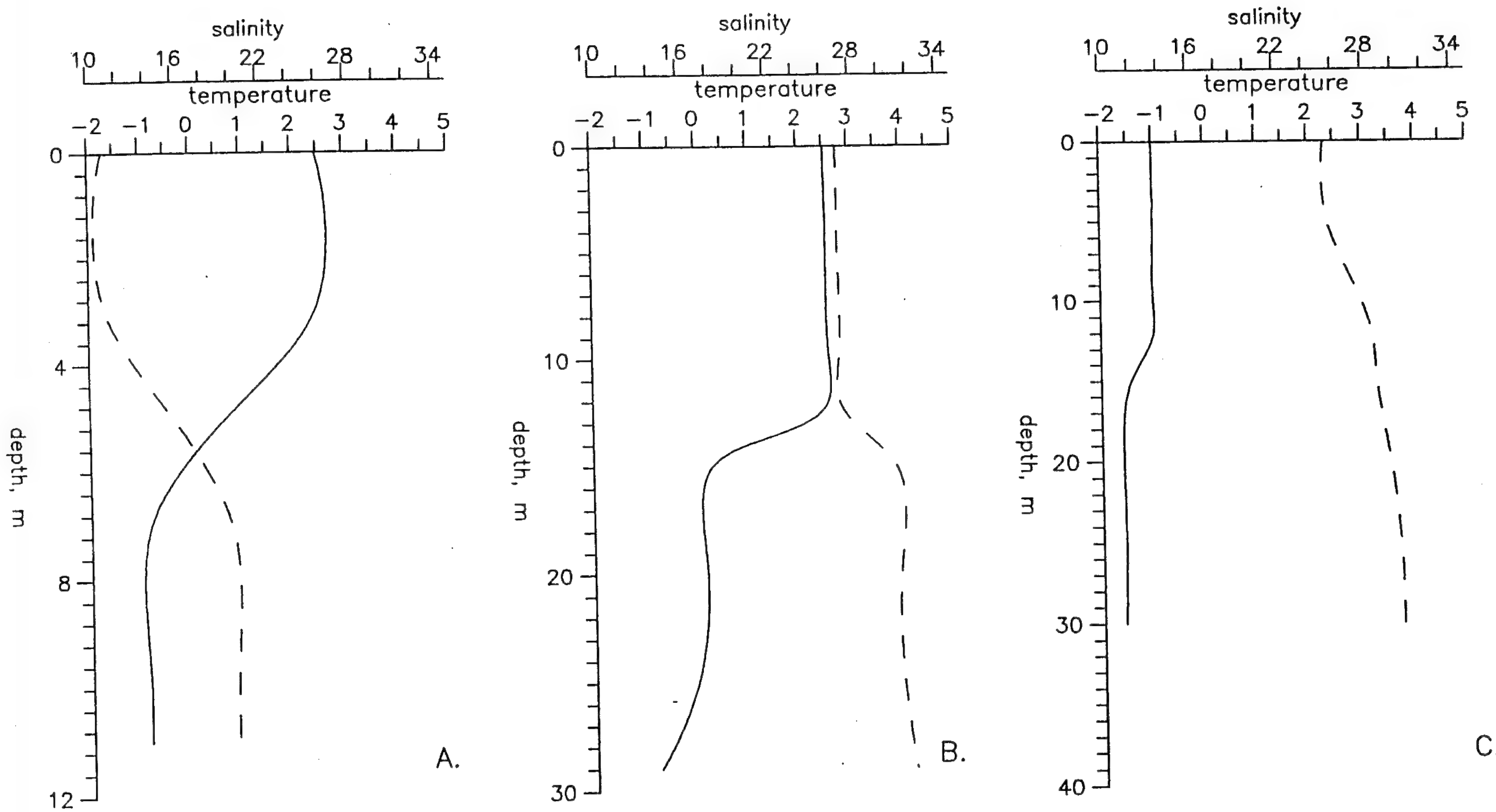


Fig.3.12. Vertical water temperature and salinity profiles in summer in different parts of the Laptev Sea.
a - south-western, b - south-eastern, c - northern part

Table 3.4

Main characteristics of the water masses
of the East-Siberian Sea

Water masses		Surface Water of Arctic Basin	Surface Water of East-Sib. Sea	River's Water	Pacific Water
Winter	Temperature ^0C	-1.80	-1.40	-	2.25
	Salinity $^0/_{00}$	32.00	25.00	-	34.98
Summer	Temperature ^0C	-1.80	-1.40	11.70	2.25
	Salinity $^0/_{00}$	32.00	22.00	0.50	34.98

East-Siberian Sea, and Fig. 3.13 [*Dobrovolskiy, Zalogin 1982*] shows the main areas of their extent for the summer and winter periods of the year. Table 3.5 indicates the character of the processes, affecting the water masses of the East-Siberian Sea [*Nikiforov, Shpaikher 1980*].

Table 3.5

Correlation coefficients between the inflow and salinity of the surface waters into the East-Siberian Sea

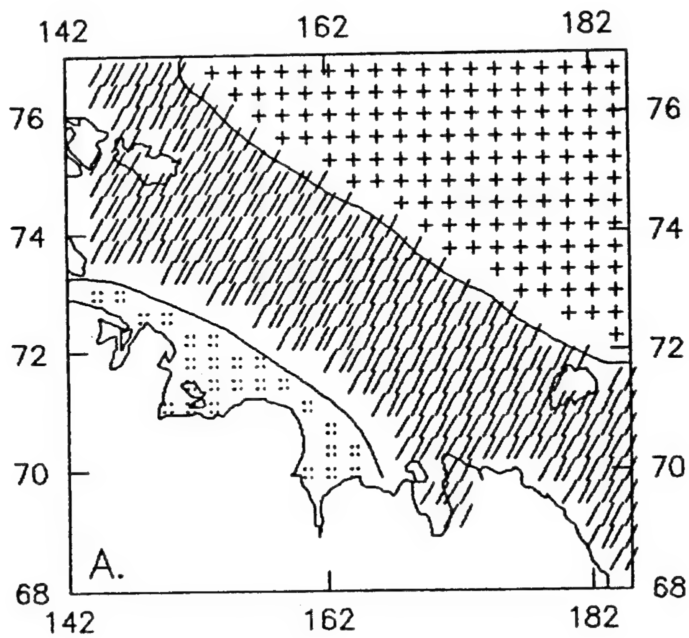
Salinity	Western part of the sea		Eastern part of the sea	
	Pacific Water's Inflow	Kolyma's Run-off	Pacific Water's Inflow	Kolyma's Run-off
in synchro- nous way	-0.46	0.44	0.03	0.19
in a 1 year	-0.33	0.45	0.17	0.21
in a 2 years	-0.05	0.59	0.44	0.12
in a 3 years	0.31	0.56	0.73	0.12
in a 4 years	0.62	0.38	0.82	0.18
in a 5 years	0.79		0.73	

3.5. Hydrochemical regime of the East-Siberian Sea

The hydrochemical structure of the East-Siberian Sea is still inadequately studied, particularly with regard to the summertime due to a difficult access for the expedition vessels. Only preliminary conclusions can be made due to the paucity of data.

The run-off of the Indigirka and Kolyma rivers, the position of the ice massifs and water exchange with the Arctic basin and adjacent seas play an important role in the formation of the hydrochemical fields in summer.

Oxygen concentrations in the surface layers are observed



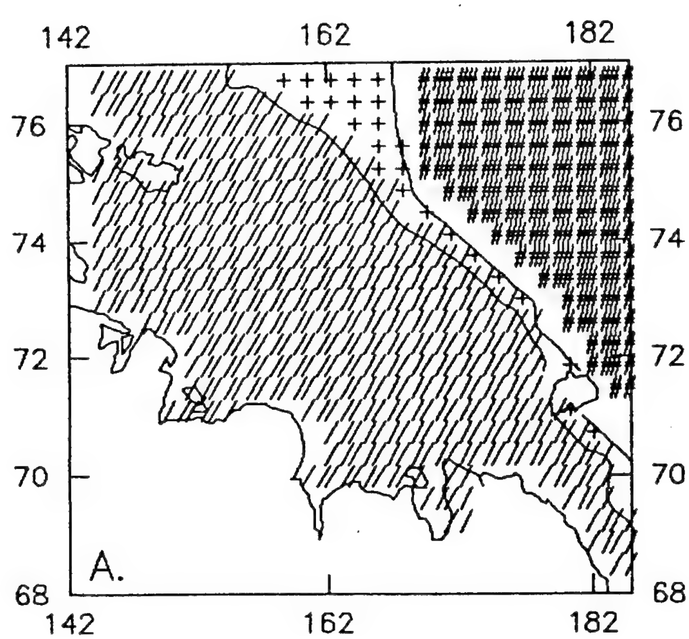


Fig.3.13. Distribution of water masses in the surface layer in the summer (a) and winter (b) periods

::: - river water, ### - Pacific water,

// // - surface water of the East-Sibirian Sea,

+ + + - surface water of the Arctic Basin.

[Nikiforov, Shpaikher 1980]

within 0.7-0.8 mg-a/l during the saturation of a 5-10 m layer up to 100-105%. Maximum values are typical of the regions, freshened by melting ice.

At the near-bottom levels the oxygen concentration decreases up to 70-75% of saturation. One should note the effect of the Pacific Ocean layer off the continental slope in the northern sea regions. The inflow of Pacific water into these regions is accompanied by the decrease of the oxygen concentration at the near-bottom levels up to 40-50% of saturation.

The silicon content in the surface layer in summer is 20-30 μMol/l, in winter it increases up to 35-40 μMol/l. The water flow from the Chukchi Sea is very important in supplementing the supply of nutrients in the surface layer of the East-Siberian Sea.

The phosphate concentration in the summertime is observed within 0.25-0.50 μMol/l, with the minimum content being typical of the marginal zone similar to the other Arctic seas. With depth the concentration decreases up to 0.75-1.0 μMol/l.

Annual variations of hydrochemical parameters are the same as in the adjacent seas, and the vertical structure changes in the same way.

3.6. Wind-induced waves in the East-Siberian Sea.

The wind-induced waves in the East-Siberian Sea are weakly developed due to its ice cover extent and a shallow character.

With the ice retreat northward during the period from July to September the occurrence frequency of strong waves increases, reaching a maximum in September. In mid August in the western part of the sea there appear comparatively large areas of open water, where at north-west winds with the speed up to 20 m/s strong waves can develop with a maximum wave height up to 4 m.

At north-east winds the wave height in this region is not more than 2.5 m.

In September when the ice edge retreats to the north the western part of the sea up to meridian of the Kolyma river mouth becomes ice free and the maximum wave heights in this region can reach 5 m.

During the years when the ice edge retreats far to the north and west strong waves develop in the region between parallels 71^0 and 73^0 N. The waves in this region move mainly from the east and south-east; the height of the waves, moving from the west is not large.

The data on the occurrence frequency of the waves are given in Table 3.6 [*Wind and Waves in the Oceans and Seas 1974*].

Table 3.6

Occurrence frequency of the waves for the East-Siberian Sea.

Navi-gation period	Prevailing direction	Occurrence frequency of the waves, % at the wave height, m				Wave elements		
		0-3	3-5	5-7	>7	Highest height m	Len-gth m	Period sec
VIII	from NE to E nonstability	96	4	0	0	4.8	87	7.6
IX	From SW in western part to NW in eastern part nonstability	95	5	0	0			

3.7. Water exchange

The water balance of the East-Siberian Sea is composed of its water exchange through the straits and open sea boundaries with the adjacent oceanic and sea areas, river run-off, evaporation and precipitation.

The average annual volume of the river run-off into the East-Siberian Sea is about 200 cu.km or less than 0.01 Sv. The amount of precipitation (about 20 cm a year) is a little more than the annual evaporation volume.

An approximate estimate of the water exchange with the Laptev, Chukchi Seas and the Arctic Basin is given in Table 3.7. [*Shpaikher, Fedorova 1978*].

Table 3.7

Mean annual water exchange of the East-Siberian Sea

Inflow	Discharge		Outflow	Discharge	
	cu.km/year	Sv		cu.km/year	Sv
Laptev Sea	$3.24 \cdot 10^3$	0.10	Laptev Sea	$3.24 \cdot 10^3$	0.10
Chukchi Sea	$8.8 \cdot 10^3$	0.26	Chukchi Sea	$6.6 \cdot 10^3$	0.20
Arctic Basin	$9.23 \cdot 10^3$	0.28	Arctic Basin	$11.43 \cdot 10^3$	0.34

One should note an approximate character of the estimates given in connection with a significant interannual, interseasonal and intraseasonal variability of the water flows through the straits. The results of numerical modeling show a significant synoptic variability of the values and direction of the water flow between the East-Siberian and Chukchi Seas through Long strait [*Kulakov 1993*].

3.8. Water circulation of the East-Siberian Sea

The characteristics of the non-periodic currents of the East-Siberian Sea is given to the currents in the summertime (August-September).

The characteristics is made mainly on the basis of publications.

The currents of the East-Siberian Sea have been inadequately investigated due to a large ice cover extent of the sea even in summer; it is difficult to obtain field data on currents because of ice.

The non-periodic currents can be considered in the first approximation as a sum of two main components: permanent currents

and wind-driven currents.

3.8.1. Permanent currents

Permanent currents do not depend on the wind, acting at a given time moment. The field of permanent currents of the East-Siberian Sea is formed under the effect of large-scale natural factors, the main of which are as follows: location and intensity of the centers of atmospheric action - the Aleutian and Icelandic Lows and the Arctic High; secondly - water exchange with the Arctic basin and the Laptev and East-Siberian Seas. In the eastern sea region the currents in summer are also affected by the Kolyma river run-off.

Due to their relative stability in space and time, permanent currents serve as a basis of sea water circulation, which has a large influence on all occurring hydrological processes.

The diagram of permanent currents in the surface layer of the East-Siberian Sea (Fig. 3.14), constructed by Pavlov mainly from published data [*Atlas of the oceans. The Arctic Ocean 1980; Baskakov et al. 1987*] shows a well-defined coastal current going from west to east through Long strait to the Chukchi Sea. The water inflow from the Laptev Sea through Sannikov strait is also well-pronounced. As to the cyclonic water gyre, so typical of all the seas of the Northern Hemisphere (except for the Aral Sea), it is shifted to the eastern part of the East-Siberian Sea, with the center in the vicinity of the Wrangel island. The water of the northern periphery of the gyre generally moves to the north-west and mingles with the Transarctic Current, going from east to west. The speeds of permanent currents, as is seen from Fig. 3.14, are small and only in some parts exceed 5 cm/s.

Interannual water circulation changes in the East-Siberian Sea are, first of all, related with the corresponding shifts of the Aleutian and Icelandic Lows of atmospheric pressure [*Gordiyenko, Karelin 1945; Soviet Arctic 1970; Shpaikher, Fedorova, Yankina 1972; Nikiforov, Shpaikher 1980*].

During the years when the Icelandic Low is prevalent (see Fig. 1.23.a) there is an enhanced eastern coastal current in the East-Siberian Sea, as well as the water inflow from the region of the New-Siberian islands.

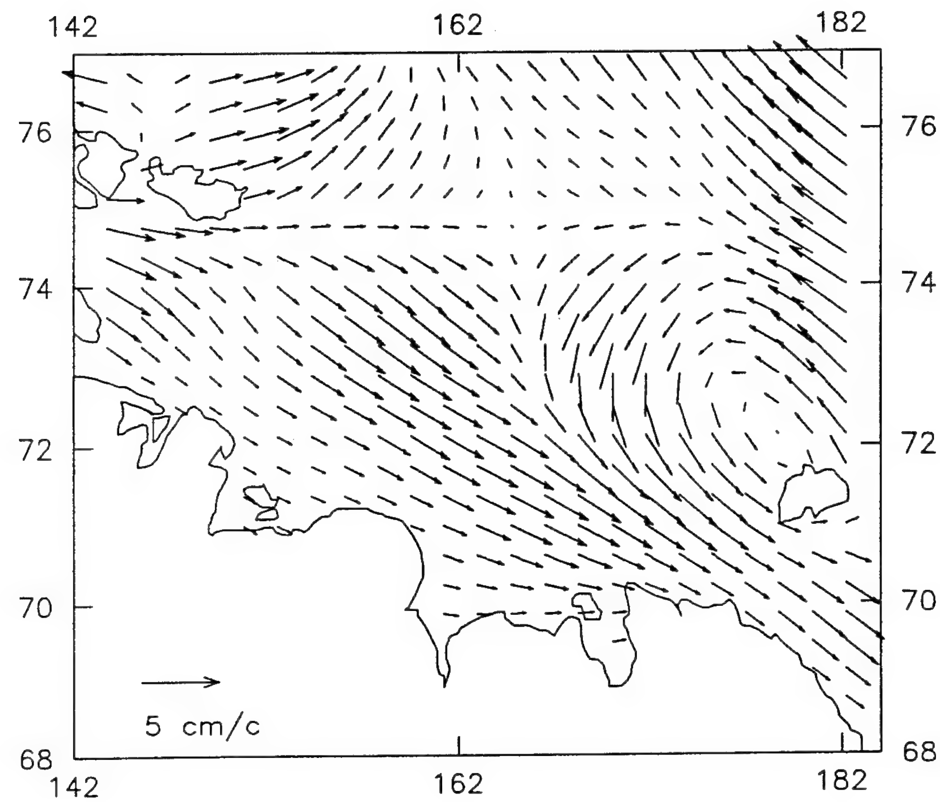


Fig. 3.14. A scheme of permanent currents in the surface layer of the East-Siberian Sea.

During the years of the dominating influence of the Arctic High (see Fig. 1.23.b) the flows going northward prevail on the whole in the East-Siberian Sea.

3.8.2. Wind-driven currents

The wind-driven currents are induced by the acting wind and they are subjected to a rapid variability in accordance with the changes of the wind direction and speed.

The wind-driven currents in the East-Siberian Sea are formed under the effect of cyclones both of the Atlantic origin, coming, although not very frequently, to the western sea region, and of the Pacific origin, penetrating the eastern sea region [*Dobrovol'sky, Zalogin 1982*].

In the coastal band of the East-Siberian Sea the wind-driven surface currents, going in the latitudinal direction - from west to east and from east to west, prevail. Thus, west and south-west winds form a warm coastal current, which spreads from Kolyma Bay eastward to Long strait [*Shpaikher 1963*]. In the area from the Shelagsky Cape to Long strait, as is indicated by the analysis of field data on currents, wind and atmospheric pressure, the wind-induced surface current goes westward at eastern atmospheric transports and anticyclones, the center of which is located over this sea region.

3.9. Tides

One observes regular semi-diurnal tides in the East-Siberian Sea. They are induced by a tidal wave, which enters the sea from the north and moves to the mainland coast. Its front is extended from the north-north-west to the east-south-east from the New-Siberian islands to the Wrangel island. A map of cotidal lines, obtained by means of modelling [*Proshutinsky 1993*] is presented in Fig.3.15.

The tides are most pronounced in the north-west and the north where the tidal wave just enters the sea limits. With the motion to the south they attenuate, as the ocean tidal wave is damped significantly in the shallow area, that is why on the segment from Indigirka to the Shelagsky cape the tidal level

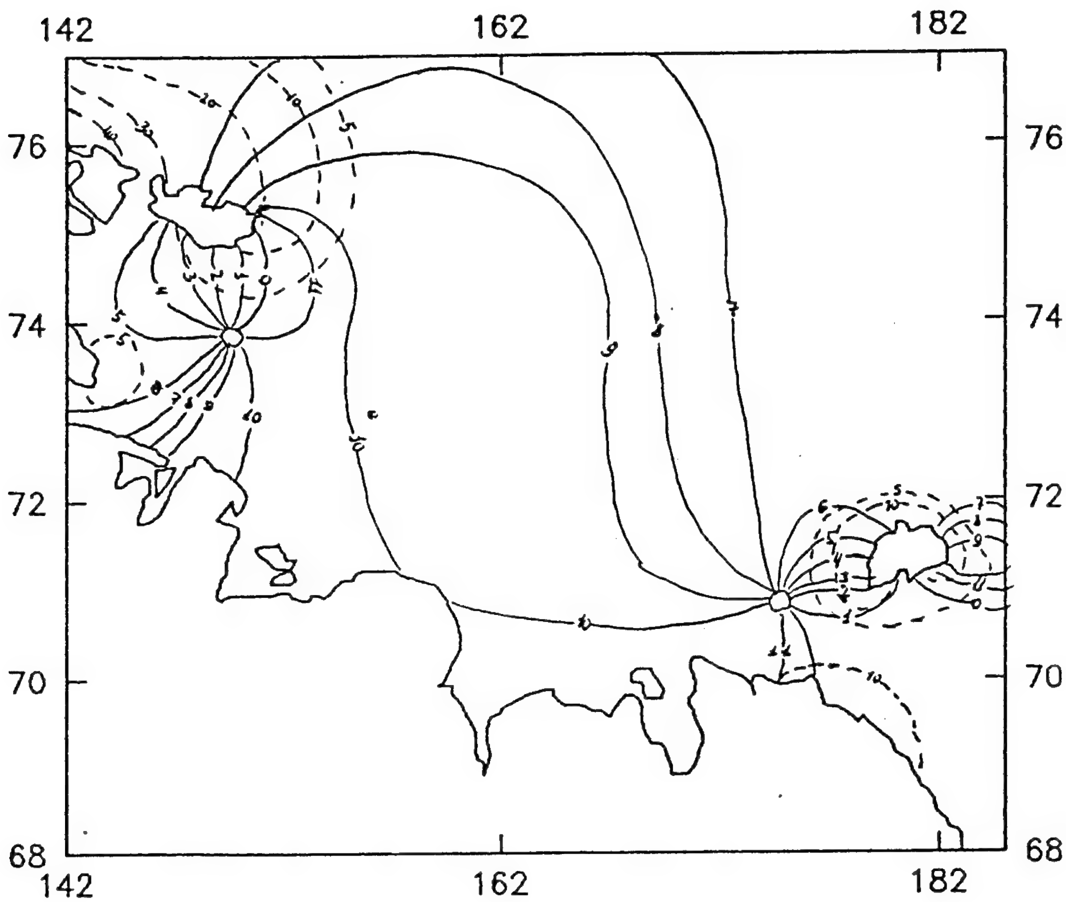


Fig. 3.15. A scheme of the M2 tidal wave propagation
[Proshutinskiy 1993]

oscillations are almost unnoticeable. Westward and eastward of this region the tide value is also small - 5-7 cm (Fig.3.16). In the Indigirka mouth the configuration of the shores and the bottom topography contribute to the tide increase up to 20-25 cm [*Soviet Arctic 1970*].

3.10. Level regime of the East-Siberian Sea

The surge phenomena with level oscillations being often 60-70 cm are very distinct in the summer season. In the Kolyma mouth and Dmitry Laptev strait they reach the values of 2.5 m, maximum for the entire sea (Fig.3.16). A rapid and sharp change of the level positions - is one of the typical features of the coastal sea regions. The character of seasonal level changes in the East-Siberian Sea is actually the same as in the Laptev Sea (Fig.3.17) [*Dobrovolskiy, Zalogin 1982*]. A minimal level height is observed everywhere in April, the maximal - in July. The climatic level changes in the East-Siberian Sea also have a positive trend (Fig.3.18), but their values are smaller than in the Laptev Sea. The most significant periods in the range of seasonal and interannual level changes in the East-Siberian Sea similar to the Laptev Sea appear to be a half year and 11 years (Fig. 3.19).

3.11. Ice regime in the East-Siberian Sea

The East-Siberian Sea is considered to be the most ice-infested among the seas of the Siberian shelf. It is completely ice covered from October-November to June-July. As compared with the other Arctic seas, the ice import from the central Arctic Basin prevails in the East-Siberian Sea. A characteristic feature of the ice cover of the East-Siberian Sea is a considerable development of fast ice in winter. The fast ice limit roughly coincides with the 25 m isobath (Fig.3.20.b) [*World ocean Altas, volume 3, Arctic Ocean 1980; Romanov 1992*]. The fast ice thickness reaches 2 m. In the west and the east of the sea, northward of the fast ice limit large areas of open water and young ice are formed, the so called recurring flaw

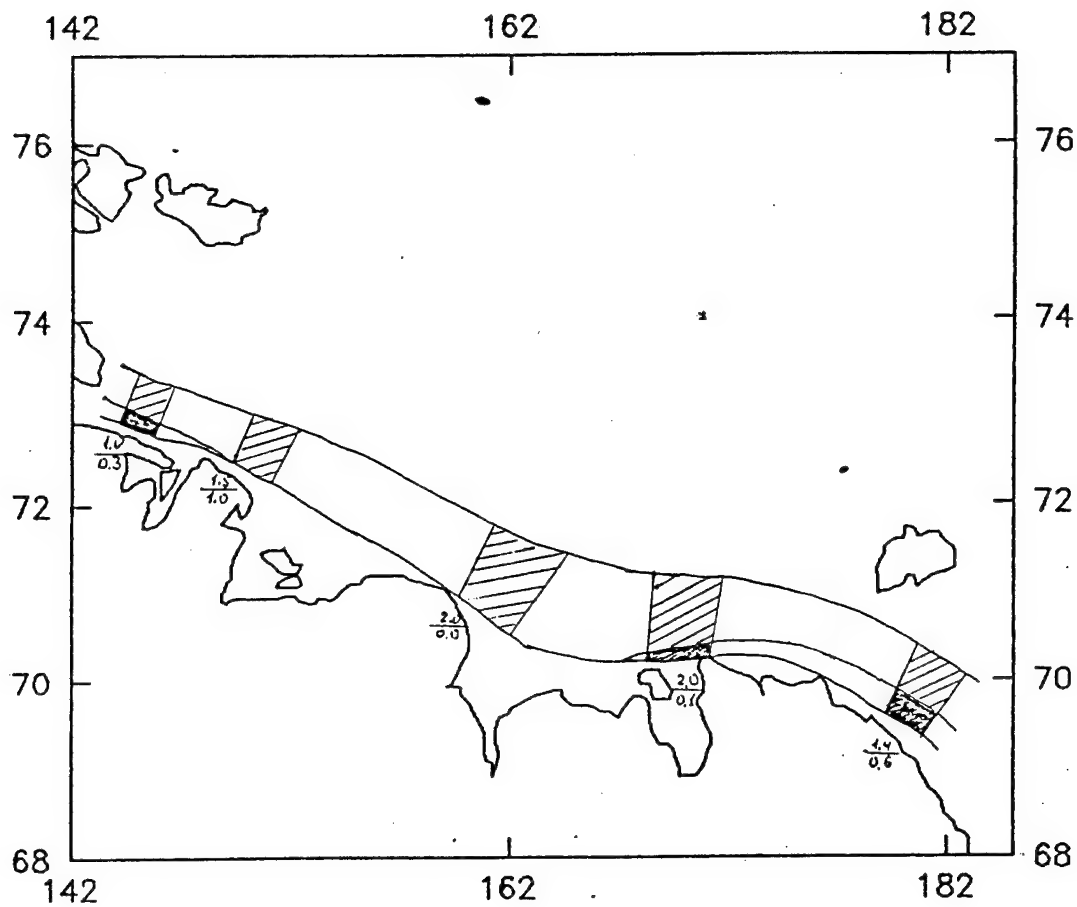


Fig. 3.16. Mean values of the storm surges, m (numerator)
and tides, m (denominator).
[Soviet Arctic 1970]

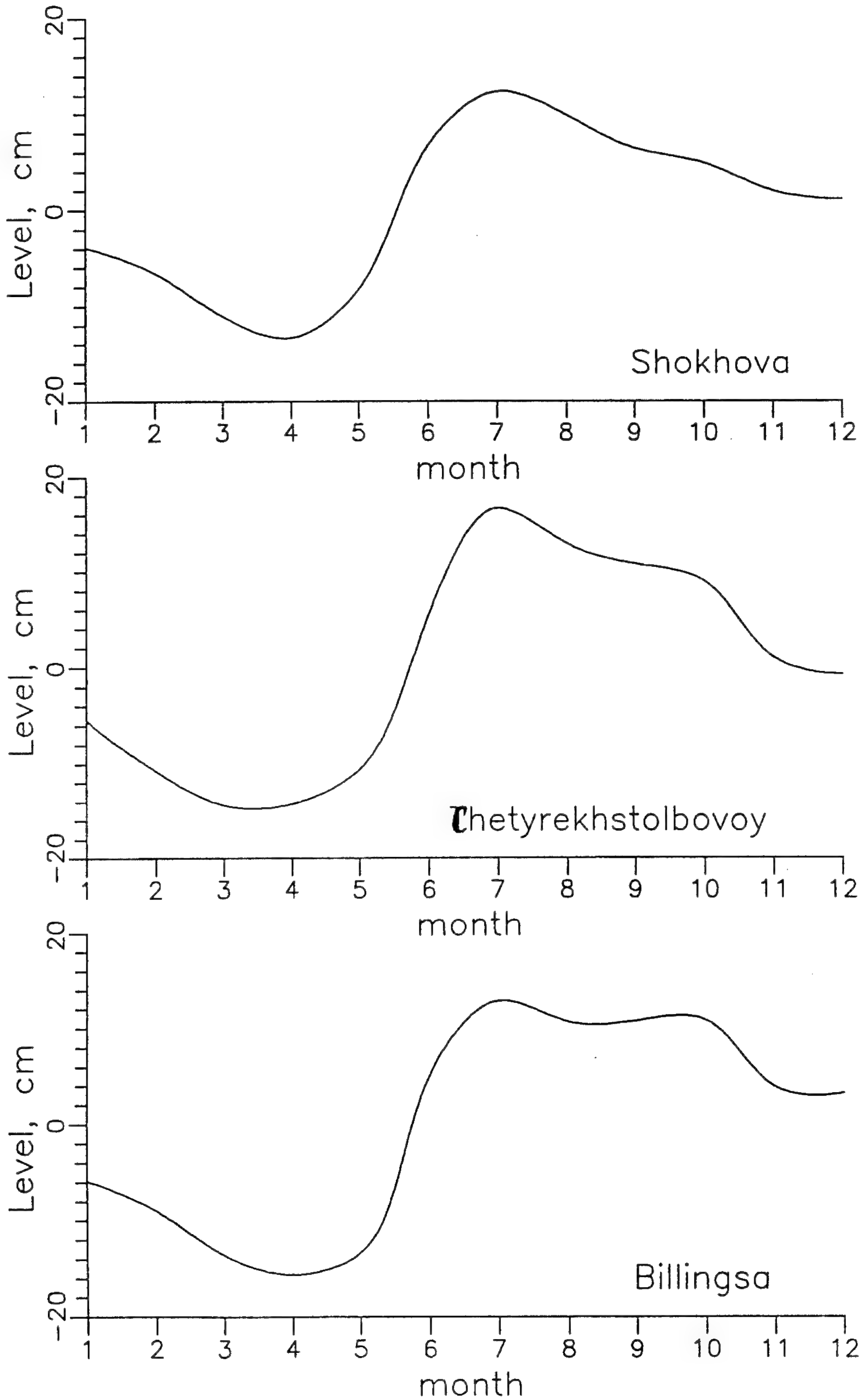


Fig. 3.17. The interannual change of mean multiyear sea level in the deviations from mean annual one according to the observations at the Shokova, Chetyrekhstolbovoy islands and Billingsa Cape

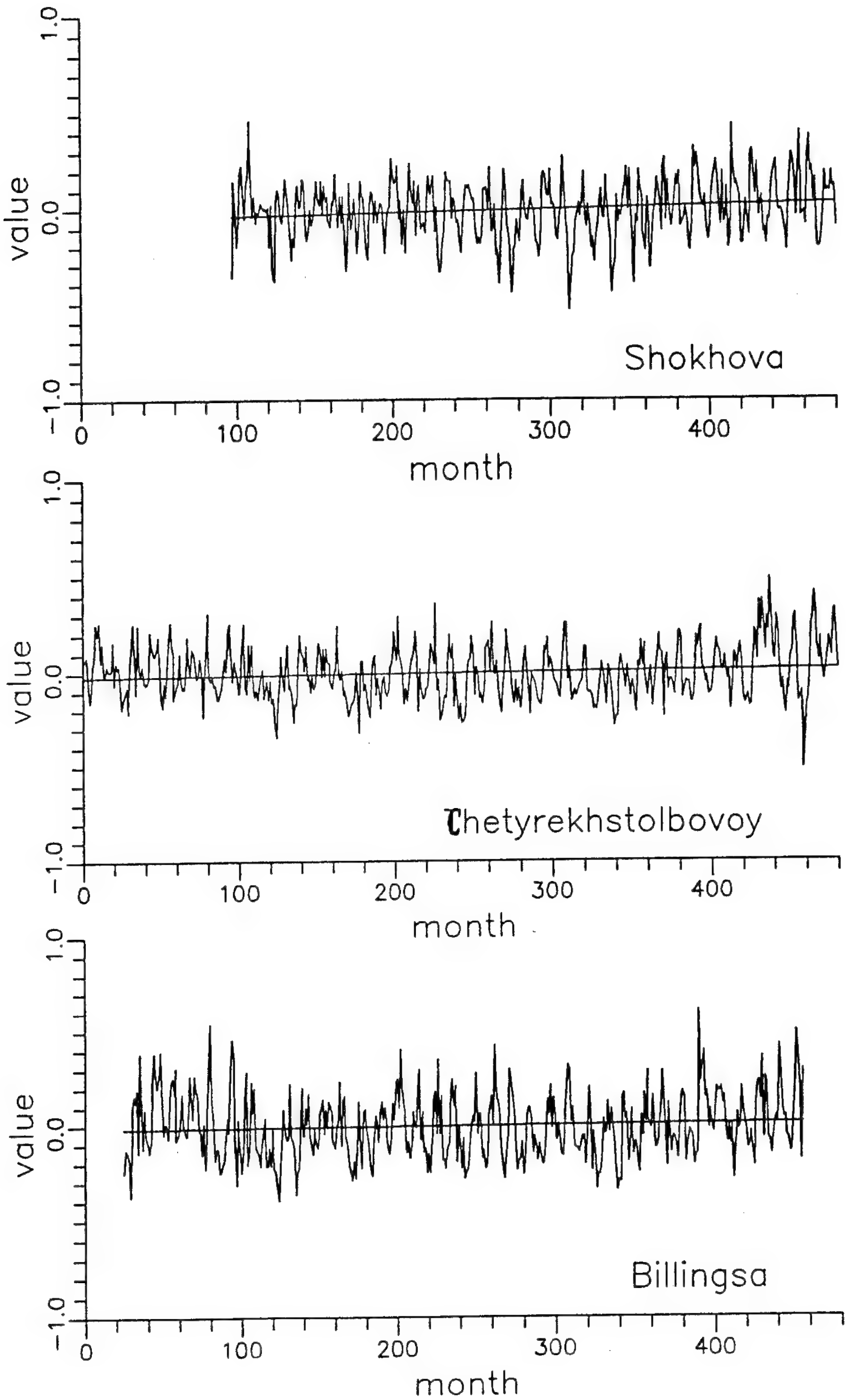


Fig. 3.18. Mean monthly oscillations at the points of the Shokhova island, Chetyrekhstolbovoy island and Billingsa Cape from the beginning of the observation period (January, 1953) and a linear climatic trend

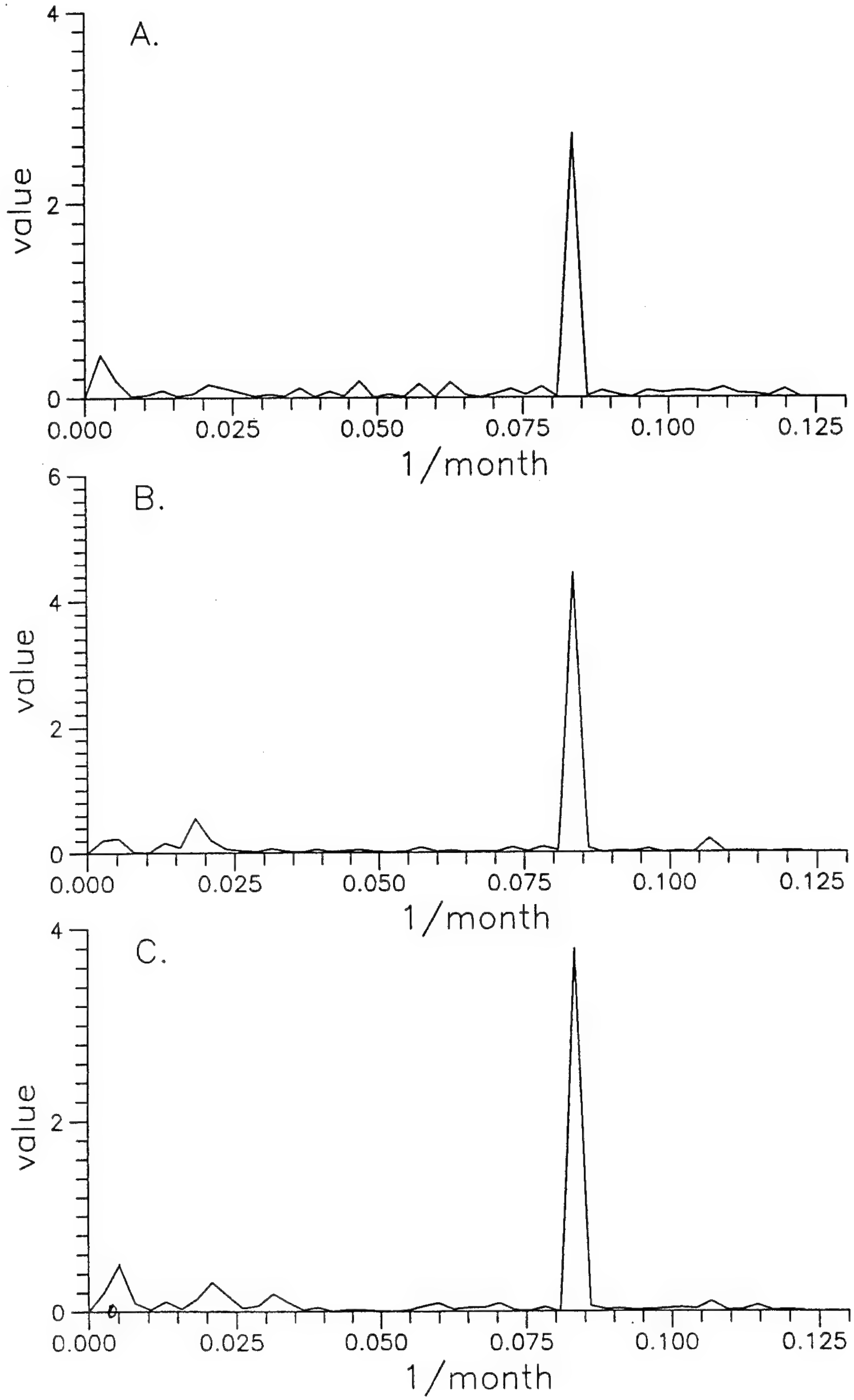


Fig. 3.19. Spectrogram of mean monthly oscillations at the Shokhova island (a), Chetyrekhstolbovoy island (b), Billingsa Cape (c)

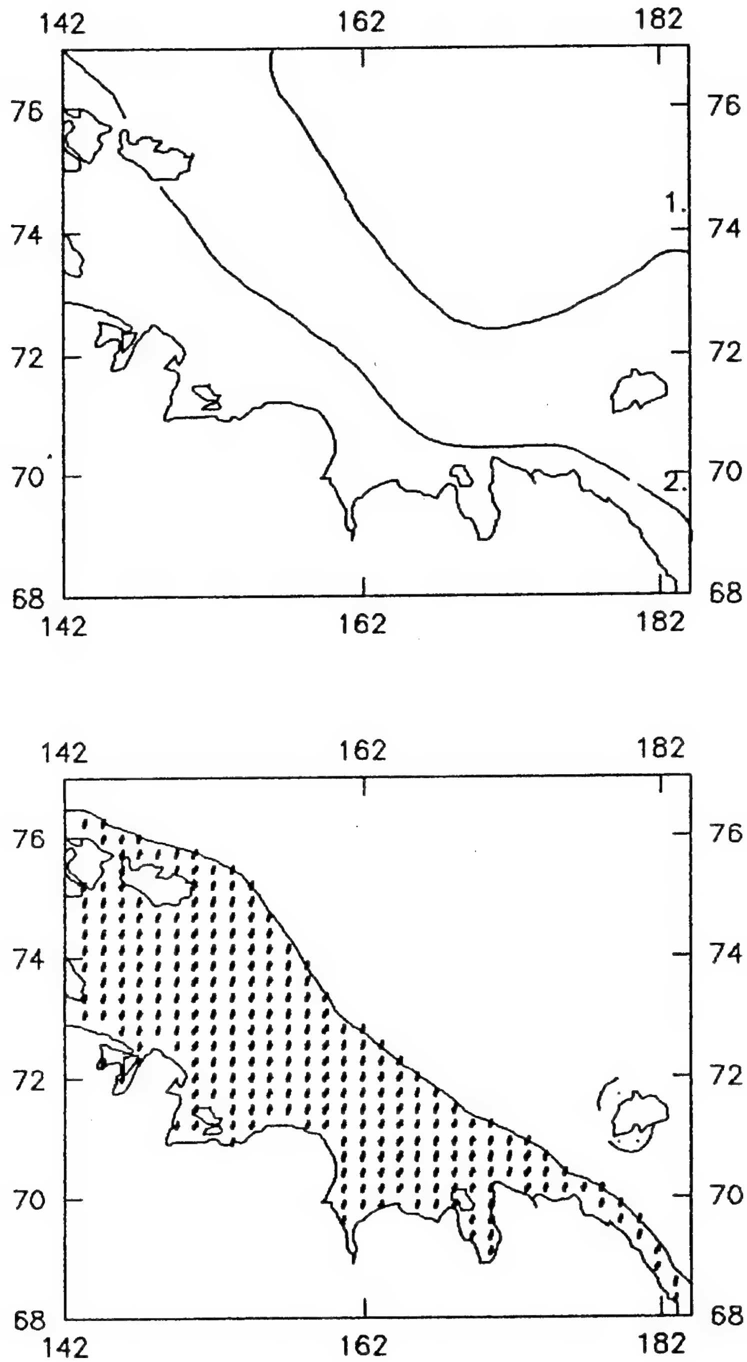


Fig. 3.20. Ice cover of the East-Siberian Sea

a - mean multiyear (1) and maximum (2) northern position of the drifting ice edge in the summer

b - the ice cover structure of the East-Sibirian Sea in the winter

::: - zone of regular behind-fast polynyas;

- fast ice; - drifting ice.

[Soviet Arctic 1970]

polynyas. The position of ice edge in the summertime is presented in Fig.3.20.a [*Dobrovolskiy, Zalogin 1982; World ocean Altas, volume 3, Arctic Ocean 1980*]. As a rule, in summer the north-eastern East-Siberian Sea is covered by heavy multiyear ice, which in some years almost joins the mainland coast.

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Under contract to the Polar Science Center at the Applied Physics Laboratory, University of Washington, the Arctic and Antarctic Research Institute in St. Petersburg, Russia, has written a review of the hydro-meteorological regime of the Kara, Laptev, and East Siberian seas, using available Russian and foreign references, data from international expeditions, and modeling results. This work was supported by the Arctic Nuclear Waste Assessment Program of the United States Office of Naval Research as part of a study of river plumes on the Russian continental shelves. It is the first step in a joint project aimed at determining the likely distribution of radionuclide contaminants by Russian river plumes through a coordinated effort of data analysis and modeling. The review suggests that river plume circulation on the Russian shelves provides a manifold for distributing contaminants to the whole Arctic Basin and, because of the tendency for eastward along-shore flow in the Kara, Laptev, and East Siberian seas, a possible direct pathway for contaminants to reach Alaska.

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